EYE MOVEMENTS
From Physiology to Cognition

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PREFACE

This book contains edited versions of the majority of the papers and posters presented at the Third European Conference on Eye Movements, held at Dourdan, France, from 24 to 27 September, 1985.

The study of eye movements is of course a research field in its own right. But eye movements have an additional particularity, which is that they can be used as a tool to reveal covert perceptual and cognitive processes. This explains why workers with many different research interests, ranging from the fundamental to the applied, are concerned with eye movements. The conference's purpose was to allow these workers to exchange viewpoints.

In attracting participants from a wide range of disciplines, we were continuing in the tradition of the two previous European Conferences on Eye Movements, held in Bern in 1981 and in Nottingham in 1983. The number of participants at these conferences has increased rapidly since the first conference, rising from 100 through 150, and reaching 250 at the present conference, with 20 countries being represented.

The conference was organised into symposia spanning eye movement research from the neurophysiological to the cognitive and applied levels. Among these, the symposium on Saccade Programming was the largest at the conference. One of the reasons for this was undoubtedly the excellent organisation by John Findlay and Zoi Kapoula. A further reason lies in the increasing success of classical biocybernetic models describing the mechanical properties of eye saccades, as studied behaviourally, in explaining and motivating neurophysiologal research into the saccadic system. Testifying to this, many of the papers presented at the Saccade Programming Symposium concerned behavioural evidence pertinent to study of the neurophysiologically known pulse generation system. Also relevant to biocybernetic modelling of eye movements were a number of papers concerning the question of how eye position is represented in the visual system. This determines how the eye saccade will adapt to a change in target position, and also how movement perception will depend on eye movements. Another centre of interest at the Programming Symposium concerned the cognitive factors involved in saccade programming. These factors are essential in determining which among several targets should be aimed at, and also in controlling the way a smooth pursuit movement will follow a predictable target.

Adaptability is a fundamental property of biological systems, as these must at the same time be sufficiently stable in their functioning to guarantee fast and efficient responses to surrounding sollicitations, but also sufficiently flexible to adjust to changing constraints and new demands for survival. A number of identifiable subsystems take part in eye movements: the saccadic system, the smooth pursuit system, and the various vestibular and optokinetic reflexes. Changes in oculomotor behaviour can occur through adaptation within a given subsystem or by different modes of interaction between subsystems. This latter type of adaptation is important in man, for whom cognitive factors play a role. In the Symposium on Adaptation in the Oculomotor System, a first session concerned adaptation (induced by experimental manipulations or by pathology) within the saccadic system, either with reference to cybernetic models, or to physiology. A second session contained a few papers on the smooth pursuit system, but mainly was concerned with interactions between subsystems, particularly eye-head coordination. As was the case for the symposium on Saccade Programming, the Adaptation Symposium showed the usefulness of a dialogue between biocybernetic models and physiology or pathology.

The symposium on Scanning was divided into papers attempting to model parameters of ocular exploration, and papers describing scanning behaviour in cognitive tasks and reading. Our idea in this symposium was to encourage participants to bridge the gap between theory and observation. While biocybernetic models study the saccade triggered by an isolated target, when considering the sequence of saccades that the eye makes in exploring a complex scene, it becomes necessary to take account of global scanning strategies (for example, in reading, from left to right, line by line). In addition a process of selection of targets among non-targets must intervene; further, pre-processing of information in non-central vision will take place. These factors were considered in some of the theoretical papers, although these were limited to relatively simple situations, such as search for a letter in a string of letters, or scanning a sequence of dots. The more descriptive papers considered more complex situations, for example scanning of stationary or moving images, reading, or eye movements during problem solving or aesthetic judgements.

In order to progress, research on the scanning of visual scenes now needs a theory of how humans recognize such scenes. This problem is less acute in the study of reading: here the objects to be recognized are describable in terms of well-defined units (letters, words...). Further, well-developed linguistic theories describing how these units combine (lexical structure, syntax, semantics) give us a description of the objects being looked at. Finally an abundant literature in experimental psychology is concerned with letter and word perception, and psycholinguistics has for many years been concerned with lexical access and sentence comprehension. Reading is thus a sort of microcosm of visual perception in which the study of eye scanning may be more profitable than in the wider, less well understood domain of visual scenes in general. At the present conference, a special topic within reading research, namely Lexicons and Languages, was chosen as a point of interest. The first session was aimed at the problem of differences between languages, with particular reference to languages written in non-european alphabets such as Japanese and Arabic. A thorough review of the main writing systems is provided at the beginning of the section as a background to the eye movement studies. A second, more general session was concerned with the influence of typography, task demands, and ambiguity on sentence processing as measured by eye movements.

The symposium on The Usefulness of Eye Movements in Ergonomics and Applied Studies attracted fewer papers than we had hoped. There were papers on automobile dashboard design, improving performance in sport, of doctors in radiological diagnosis, of postal and bank workers. It appears that eye movements, at present, give little more information about performance than can be obtained by verbal questioning. Again, as was the case for Scanning, the problem is a lack of a satisfactory description of the tasks being studied and of the actions that the subjects must undertake to accomplish them. Without these, eye movement data are too complex to interpret.

In the symposium on Measurement Techniques it was apparent that current research generally concerns, not new techniques, but ways of improving the reliability of existing ones. In particular, the real time use of microcomputers to calibrate and control measurements allows increased accuracy and ease of use. A number of not-too-expensive commercial systems were demonstrated at the conference.

In conclusion, it is interesting to compare the contents of the present conference with that of its predecessors in Europe and the United States. First, we noted a decrease in the number of submitted papers on applied topics such as ergonomics and medecine, as well as in the fields of visual development of the child and of pathology. (It is of course difficult to know whether this corresponds to moroseness in these fields, or to our having insufficently publicized the conference in these fields). Second, we noted an increasing interest in interdisciplinary studies that unite biocybernetic models with neurophysiology and that take account of cognitive factors.

Finally, it is clear that eye movement research remains an expanding domain.

Acknowledgements

The conference was supported financially by the Centre National de Recherche Scientifique, Electricité de France (Club Lumière), Essilor, Union Nationale des Syndicats d'Opticiens de France, and Société d'Optique Physiologique. We would particularly like to thank the symposium organisers: John Findlay, Zoi Kapoula, Gabriel Gauthier, Alain Berthoz, Bernard Pavard, Gilles Roman, James Richardson, and Michel Neboit, who helped us put together the topics, encouraged contributions in each of the domains, selected among the potential papers, and finally, proposed changes and clarifications in the final manuscripts. The success of the conference was to a great extent due to this arduous work. We would also like to thank Rudolf Groner and Alastair Gale, who, having organised the previous two conferences, gave us precious advice. The following people also gave scientific advice: D. Heller, C. Menz, J. Leplat, and C. Bonnet. Finally, the conference would not have been possible without the patient secretarial work of Marie-Denise Philomète and the excellent assistance of Jacqueline Guerre. Finally, very special thanks are due to Barbara Steinkeller, who was the organisational mainstay before, during, and after the conference, and who also helped us with the preparation of the manuscript.

J.K. O'Regan
A. Lévy-Schoen

Paris, May 1986

EYE MOVEMENTS: From Physiology to Cognition
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SYMPOSIUM INTRODUCTION : THE MODELLING OF SACCADE PROGRAMMING

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The previous European Conference on Eye Movements contained a session entitled Properties of the Saccadic Eye Movement System (Gale and Johnson, 1984). This demonstrated that the current capacities for accurate recording of saccadic eye movements and automated analysis of such records have opened up many options for scientific study. The symposium at Dourdan shows that this approach continues to be productive. Indeed the number of papers in the saccade programming symposium was so large that individual mention of all papers in this introduction is regrettably not feasible. Also study of saccadic eye movements forms the basis of much work reported in the Scanning and the Adaptation symposis.

The saccadic eye movement system has attracted the attention of workers in several different disciplines and this can only be welcome in an era of increasing fractionation and compartmentalization of knowledge. Contributions to the symposium come from engineers, physicists, physiologists and psychologists, and it is fitting that several contributors explicitly acknowledge the influence of D.A. Robinson. Robinson, as a physiologist with a background in systems engineering has pioneered the careful harmonization of engineering concepts with physiological findings. In consequence the modelling of the saccadic system that appears in the following pages is much more constrained by the realities of brain function than any comparable modelling in the past. Thus in general, rather than resulting in totally new insights, much work is concerned with fleshing out details and redressing the unfortunate overemphasis on horizontal saccades in earlier studies.

What is the physiological basis on which saccadic modelling now stands? We know, through the work on single unit recordings in animals (see e.g. Fuchs, Kaneko and Scudder, 1985), that certain cells in the brainstem are normally active but switch off for each and every saccade - the omnipauser cells. We know in turn that when these cells switch off, burst cells are released from inhibition, or at least a selection of burst cells since these, in contrast to the omnipauser cells, selectively code the spatial properties of the saccadic movement. Above all we know, following the work of Robinson (1975, 1981), how the burst cells can direct the appropriate firing in the motoneurons to move the eye and hold it in position. Thus the basic pulse generation system can be regarded as well established, although one of the most significant developments in recent years has been the demonstration by Fischer's group of different categories of saccades based on measures of latency distributions. These presumably reflect different points in time at which the pulse generator may be activated. Several papers address the issue of whether there might be more than one pulse generator, notably those by van Gisbergen, van Opstal and Roebroek, and the impressive study on the pigeon by Bloch, Lemeignan and Martinoya. Properties of the pulse generator also form the basis of the paper by Inchingolo, Spanio and Bianchi, and the posters by Galley, by Kapoula, Robinson and Hain, and by Bour, de Veth and Huygen.

Another idea introduced by Robinson was that the control of burst cells to move the eye to the target position was achieved by a local feedback loop using instantaneous eye position information. Several of the papers are concerned with the details of how this might be implemented and the general idea of a spatiotopic framework for saccade planning is discussed below in connection with predictive eye movements. Van Gisbergen et al provide further confirmation, in a very striking way, that saccades trajectories are modifiable in a target-seeking manner. Viviani and Velay carry out a psychophysical study which parallels the informative demonstration by Mays and Sparks (1980) that saccade control uses a spatiotopic signal, and the paper by Ling relates to the same issue. Roll and Roll introduce the technique of muscle vibration to discover properties of the extraocular muscle system. The partial stabilization technique of Barabanschikov shows that a bizarre form of interference with voluntary eye movement can be created when the relationship between the direction of movement of the eye and contingent direction of retinal motion is changed. However, it is interesting that small changes in this relationship pass unnoticed.

Moving upwards from the brainstem circuitry that generates the movement itself, psychophysical studies in the posters by Asten and Gielen and by van der Wildt, Flipse, Rodenburg and Keemink examine the properties of the visual system in relation to eye movements. The poster by Accardo, Inchingolo and Pensiero enriches our knowledge of the relation between latency and size of the movement which is often thought to be due to visual processing.

Amongst psychologists, saccadic eye movements are usually seen as a means rather than an end and interest focuses on their role in perception and cognition. In the area of perception particularly, the elegant work of oculomotor modellers and experimenters, along with other work in neurobiology, has currently to face criticisms from a movement, associated with the writings of J.J. Gibson (1966, 1979), which queries the relevance of laboratory based studies for understanding perception in real world environments. We believe that this attack is largely unjustified and that work in eye movements has been more sensitive than in some other areas to the biological nature of the system under study, for example in the recent emphasis on adaptive properties of oculomotor control.

Nevertheless it is necessary to be vigilant. It is easy to forget that eye movements did not evolve to scan display screens. Certain things are immediately evident when consideration is given to 'real world' eye movements. The three dimensional nature of visual space is paramount and this has the consequence that the normal visual input to the saccadic system is different in two respects from that usually considered by systems modellers. Firstly, sharply focused, small targets are unlikely to occur frequently. Secondly, targets at a different depth from the original fixation plane will show disparity; that is the retinal error signal in the two eyes will differ. When this is borne in mind, it is not too surprising that the saccadic system shows the spatial integration of the visual input found in the global effect (Findlay, 1982; Ottes, van Gisbergen and Eggermont, 1984).

Gibson's ambition to explain perceptual systems with no reference to cognitive process sometimes drove him to absurd lengths when he discussed eye movements. His claim (Gibson 1966, p.260) that shifts of fixation can be attributed to "interesting structures in the array and interesting bits of structure" answers very little. Saccadic eye movements provide an unrivalled opportunity for psychologists to investigate the microstructure of cognitive activity (or whatever name is given to the process which allows what is 'interesting' to change from moment to moment). Much of the material on cognitive control of saccades is to be found in other symposia but two papers (Coëffé and Menz and Groner) examine the tradeoff between sensory and cognitive factors in the programming of saccades to newly appearing complex targets. Both confirm the interaction that occurs between the two influences on the spatial properties of the saccades supporting the view that this is a fruitful research strategy (Findlay, 1985).

Arguably the simplest evidence of cognitive activity comes when anticipatory saccades are made to a predictable target movement. Ron, Droulez and Vieville demonstrate prediction in the saccades to acquire a moving target, thus extending the debate about the saccadic system's ability to 'take into account' target motion. It is worth noting that a recent study shows that monkeys also are capable of such a predictive ability (Newsome, Wurtz, Dursteler and Mikami, 1985). A pressing need seems to be to decide whether such predictive abilities, which seem attributable to low levels ('predictive ability in the saccadic system'), are really different from predictive abilities at higher levels. The demonstration by Zambarbieri, Schmid and Ventre is important in this context in showing that similar patterns of predictive saccadic movements emerge when the stimulus is auditory rather than visual. The concept of a general spatial framework for motor programming is very appealing. Skavenski and Hansen (1978) suggested some time ago that the same information might be used for the control of eye movements and for limb movements. The elegant results of Pelisson, Goodale and Prablanc showing readjustment of manual pointing on the basis of target error following a saccade evidently fit well into this framework, as also does the paper by de Bie, van den Brink and van Sonderen. The posters by Lecas and Vitton and by Fischer and Rogal also concern eye-hand interactions. These ideas have a significance away beyond the narrow specialisation which might appear indicated by the title of the symposium.

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DYNAMICS OF SACCADIC TRACKING RESPONSES: EFFECTS OF TASK COMPLEXITY

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The influence of task complexity on saccade dynamics was explored using three experimental paradigms: visual target, remembered target, and anti-saccade task. Main sequences were established for all three types of saccades, for two subjects. We have found that (1) anti-saccades and saccades to remembered targets have strongly reduced peak velocities, (2) these saccades typically have very skewed velocity profiles, and (3) the reconstructed neural control signals, held responsible for the generation of these saccades, are quite abnormal.

INTRODUCTION

Saccadic responses to visual targets are characterized by fixed relationships among amplitude, duration and peak velocity, the so-called main sequence (Bahill, Clark and Stark, 1975; Baloh, Stills, Kunley and Honrubia, 1975). In the human, saccades made to remembered targets (Becker and Fuchs, 1969), or to auditory targets in darkness (Zambarbieri, Schmid, Magenes and Prablanc, 1982) are known to be somewhat slower. In the monkey a similar result has been obtained for saccades to remembered targets (Hikosaka and Wurtz, 1985a). Furthermore, Hallett and Adams (1979) have noticed 'anomalous' velocity profiles in saccades away from a visual cue stimulus (antisaccades). Taken together, these findings indicate that the task and the stimulus conditions seem to influence saccade dynamics. This may imply the involvement of different supranuclear systems in the generation of these saccades. There is indeed some preliminary evidence that remembered target saccades and antisaccades are generated by a neural subsystem which is different from that responsible for saccades to a visual stimulus (Hikosaka and Wurtz, 1985b; Guitton, Buchtel and Douglas, 1985).

We have further explored the influence of task complexity on the dynamics of saccadic responses, by using three different experimental paradigms: visual target, remembered target and antisaccade task.

We found that main sequence plots are insufficient to characterize the abnormally shaped velocity profiles which we have observed. As will be demonstrated, there appears to be a strong relationship between the skewness of the velocity profile and saccade duration.

Finally, we have tried to reconstruct the neural control signals involved in the generation of these saccades, using a deconvolution method described by Van Opstal, Van Gisbergen and Eggermont (1985). The results show that the amplitude and the shape of the pulse in the reconstructed neural control signal for remembered target saccades and antisaccades is very abnormal.

METHODS

Recording of eye movements. Eye movements were measured with the double-magnetic induction method (Bour, Van Gisbergen, Ottes and Bruijns, 1984). Raw horizontal and vertical eye position signals were low-pass filtered (-3 dB at 150 Hz), digitized at a rate of 500 samples/s with a precision of 12 bits and stored in a PDP 11/34 computer. The data were corrected offline, to compensate for the static nonlinearity inherent in this method, as described by Bour et al. (1984). In humans, the double magnetic induction method has a range of 25-30 deg in all directions, with a resolution of .25 deg, or better, in the range 0-25 deg. In the presentation of the results, only the first saccade in each trial is shown in Figs. 2 through 7.

Subjects and stimuli. Four subjects participated in this study (3 male, 1 female; ages 26-42), all with normal vision. Two subjects (JVG experienced; IMF naive) were investigated extensively, the other two yielded qualitatively similar results.

Stimuli were back-projected on a translucent screen, placed at 57 cm before the subject. Background illumination was sufficiently low to make the fine exture of the translucent screen invisible. Targets were presented at five eccentricities (5, 10, 15, 20 and 25 deg) and in six directions (0, 45, 135, 180, 225 and 315 deg). In all experiments fixation and target position were indicated by a 0.9 deg green spot (5 cd/m^2). The anti-cue position was indicated by a 0.9 deg red spot (5 cd/m^2).

Three different paradigms were used: 1) Visual target (single spot paradigm): the target reappeared at a peripheral location after the fixation light extinguished. Main sequences are based on at least 5 presentations at each target position. 2) Remembered target: during fixation a target flash (200 ms) appeared, which the subject should acquire as soon as possible after disappearance of the fixation light. The fixation light was switched off 100, 400, 800 or 3200 msec after the peripheral flash was switched off. The target reappeared 1450 ms after extinguishing the fixation light, to provide feedback to the subject about his performance. Main sequences are based on at least 15 presentations at each target position. 3) Antisaccade task: at the beginning of each trial, the fixation light flashed at a rate of 10 Hz for 1 second to warn the subject of an impending antisaccade trial. After disappearance of the fixation light, a red non-target flash (200 ms) was presented, which served as a cue to the location of the target light (not yet visible). Target position was always diametrically opposite the cue flash at the same eccentricity with respect to the fixation light. After presentation of the cue flash, a pause of 1450 ms elapsed before the appearance of the target light, which enabled the subject to eliminate the remaining positional error, if any. Main sequences are based on at least 15 presentations at each target position.

In each experimental session, 2-9 stimulus sequences were presented. Each sequence consisted of either 30 anti-target trials or 30 remembered target trials, as well as 10 visual target trials. At least three different, randomized, sequences were available for both sequence-types. Anti-target and remembered target sequences were presented alternately.

Skewness of saccadic velocity profiles. Visual inspection of saccadic velocity profiles, obtained in our remembered target and anti-saccade experiments, gave us the impression that these were more skewed (asymmetrical) than velocity profiles of saccades to visual targets. Van Gisbergen, Van Opstal and Ottes (1984) have shown that there is a tight relationship between the duration of a saccade and its skewness, which can be determined by fitting a gamma function to the saccadic velocity profile.

Reconstruction of neural control signals. Horizontal saccades to the right were used in the reconstruction of the neural control signals at the motoneuron level. These control signals were obtained by an inverse method described by Van Opstal et al. (1985), assuming a second order linear plant model (time constants 150 and 12 ms).

RESULTS

Main sequence. In Fig. 1 some responses are shown to 4 target positions (10 and 25 deg left and right) for single spots (left panel), as well as for antisaccades (right panel). The manifest reproducibility of single spot saccades contrasts strongly with the variability of antisaccades in at least three respects: latency, accuracy and peak velocity.

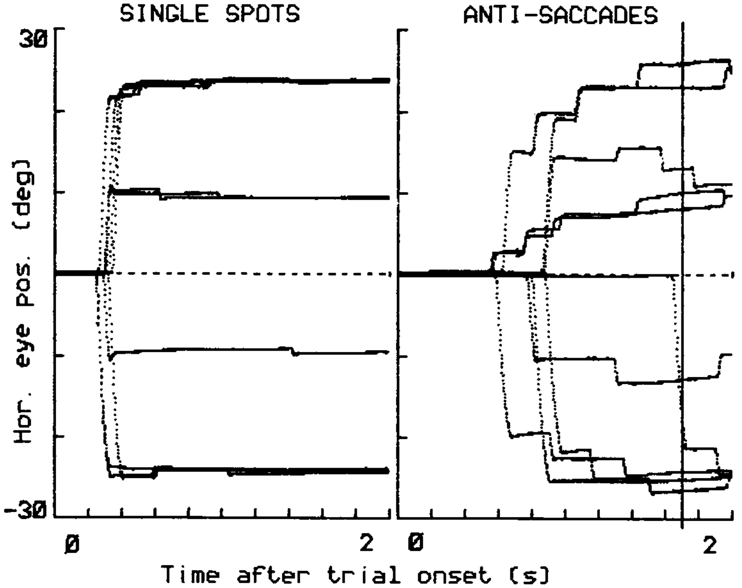

Fig. 1 Horizontal single spot saccades (left) and anti-saccades (right) to different horizontal target positions. Vertical bar in right panel indicates onset of target light. Note the difference in latency and accuracy between the conditions. Subject JVG.

Since our chief interest in this study is the main sequence, we will only consider the last item. Overall main sequences for remembered target saccades, as well as single spots, can be seen in Fig. 2 for subjects JVG and IMF. From this figure, it is obvious that saccades to remembered targets have considerably reduced peak velocities, and hence prolonged duration, with respect to single spot saccades. Also, the variability in these characteristics is increased. Anti-saccades proved to be comparable to saccades to remembered targets in both subjects. The results shown are qualitatively similar for all four subjects.

We wondered whether the slow saccades might be ascribed to reduced alertness since both in the remembered target and in the anti-saccade paradigm the saccade is made in darkness. Under these conditions, arousal may be reduced and this is known to results in slow saccades.

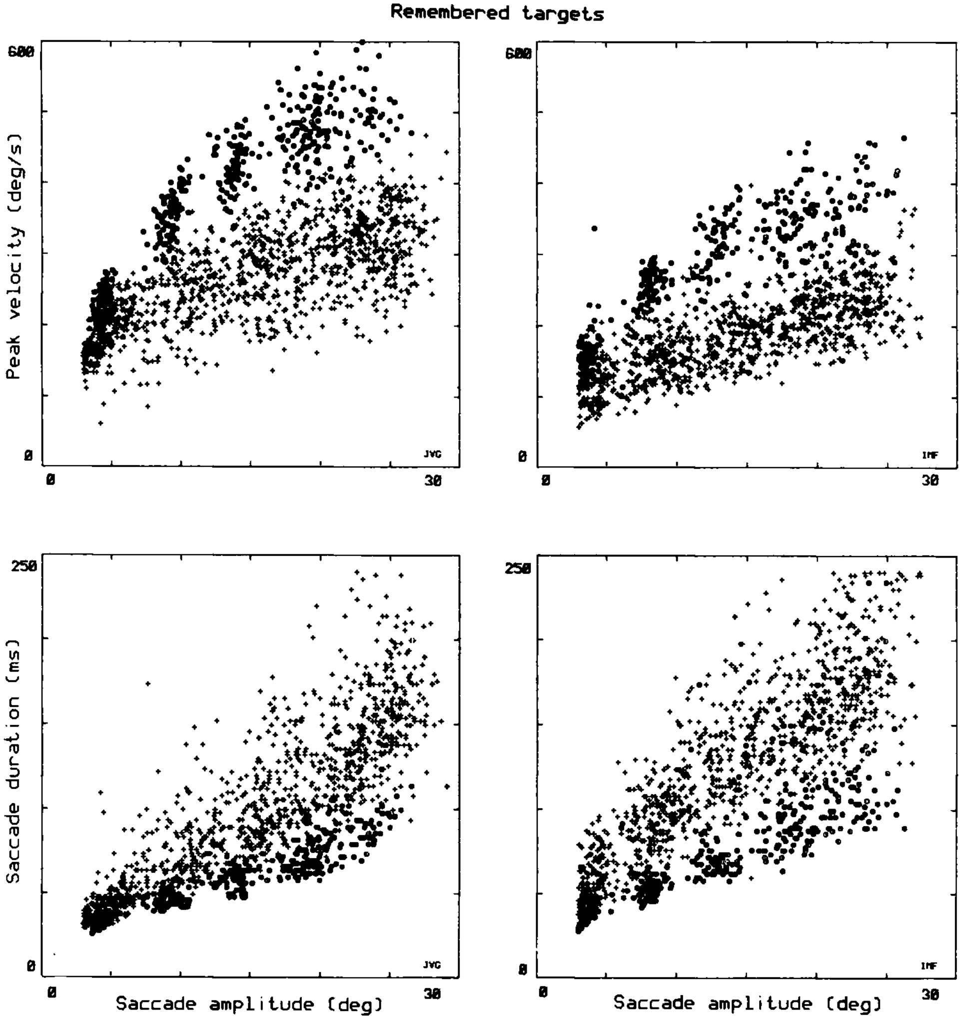

Fig. 2 Main sequence for saccades to remembered targets in subject JVG (left) and IMF (right). Meaning of the symbols: ● single spot (controls obtained in same runs), + remembered targets.

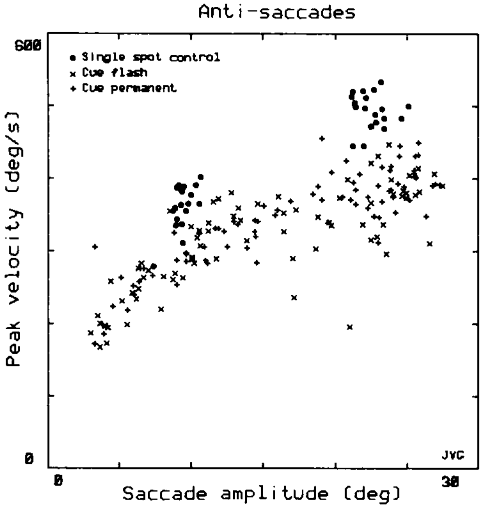

Fig. 3 Anti-saccades in the presence of a light spot (cue permanent condition) are equally slow as anti-saccades in the absence of light (cue flash condition), with respect to single spot control saccades obtained in same session. Subject JVG.

We have conducted an additional experiment in order to investigate the influence of darkness-induced drowsiness in our study. In one session, the subject was successively presented with two series of 40 normal ('cue flash') antisaccade tasks, followed by two series of 40 modified antisaccade tasks, in which the anti-cue remained on for the duration of the trial ('cue permanent'), and finally one series of 40 visual targets. Target positions were 10 and 25 deg left and right, respectively in a randomized sequence. The results of this experiment are presented in Fig. 3. It is clear from this figure that there is no difference in peak velocity between antisaccades in the 'cue flash' and in the 'cue permanent' condition. Thus, it does not seem probable that our results are caused by a decrease in arousal due to the temporary absence of a light stimulus.

Skewness. Saccadic skewness, obtained by fitting a gamma function to the velocity profile, is plotted against saccade duration in Fig. 4. The drastic difference between saccades to visual targets on the one hand, and remembered target and antisaccades on the other, apparent from the main sequences in Fig. 2, has disappeared in the duration skewness plots in Fig. 4. Instead, these plots show a tight relationship between both saccade parameters. This relationship is approximately linear for saccades lasting up to about 125 ms, and tends to level off for longer durations. Moreover, the duration-skewness relationship seems to be roughly the same for all four subjects. In contrast, the relation between skewness and saccade amplitude is quite different for remembered target and antisaccades as compared with single spot saccades (see Fig. 5). These results are qualitatively similar for all four subjects.

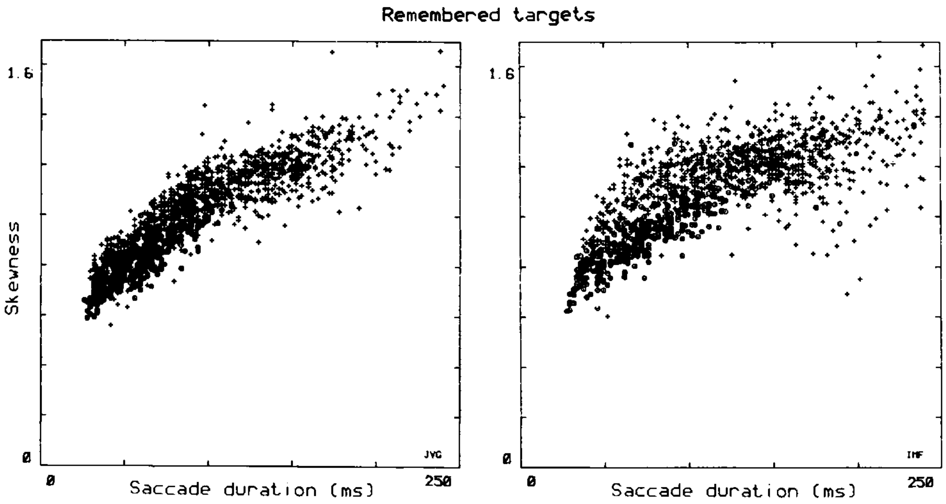

Fig. 4 Relationship between duration and skewness of saccades in both subjects for saccades to remembered targets. Meaning of the symbols: o single spot , + remembered target.

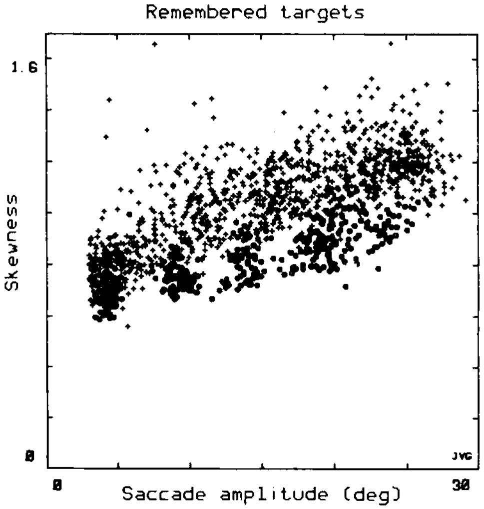

Fig. 5 Relationship between amplitude and skewness of saccades to remembered targets in subject JVG. Meaning of the symbols: o single spot, + remembered target.

Reconstruction of neural control signals. Given the decrease in peak velocity of remembered target and antisaccades, one is led to expect an associated decrease in burst frequency at the motoneuron level. Also, under the assumption of a linear plant, the differences in the shape of the velocity profiles, as expressed in the skewness parameters, may reflect shape differences in the neural control signal generated for saccades in different experimental paradigms.

For each of our three saccade types, velocity profiles and the reconstructed pulse-step signals of several horizontal 19 deg saccades are shown in Fig. 6. From this figure, it is clear that for both remembered target and antisaccades the pulse (i.e., the motoneuron burst) has reduced peak frequency, an increased duration, and is more skewed than the pulse for a single-spot saccade. In addition, it can be seen that there is greater variability in the pulse for antisaccades than for saccades to remembered targets.

DISCUSSION

Our study of saccades to visual targets (single spot saccades), remembered targets, and anti-saccades has yielded three main results:

First, saccades to remembered targets and antisaccades have main sequences that differ from those of saccades to single spots (Fig. 2), in that their peak velocities show a marked decrease with a concomitant increase in their durations. In the literature, slow saccades in the human have been reported for saccades to remembered targets in darkness (Becker and Fuchs, 1969), for sac-

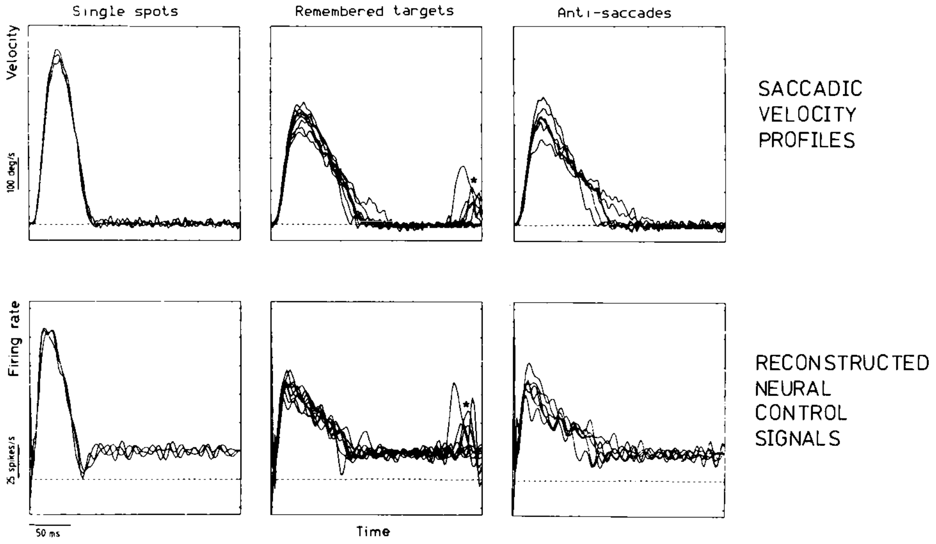

Fig. 6 Velocity profiles (upper panels) and reconstructed pulse-step signals (lower panels) for subject JVG in all three conditions for horizontal 19 deg saccades to the right. Peaks indicated by asterisks (middle column) are correction saccades.

cades to auditory targets in darkness (Zambarbieri et al., 1982), for drug-influenced saccades (Jürgens, Becker and Kornhuber, 1981; Van Gisbergen et al., 1984) and in several neurological disorders (Leigh and Zee, 1983). In some of these cases a reduced level of arousal might have caused slowing of saccades. In our study a decrease in arousal due to temporary darkness has been ruled out as a possible cause for slow saccades: having a permanenent spot of light in the subjects' visual field does not increase the peak velocity of antisaccades (Fig. 3). Also, if anything, the antitask requires subjects to be more alert to be executed properly.

Second, we have shown not only that the skewness of the saccadic velocity profile changes with amplitude (Baloh et al., 1975), but also that the skewness varies with different task characteristics: remembered target and antisaccades are markedly more skewed than saccades of equal amplitude to visual targets (Fig. 4). We confirm the finding of Van Gisbergen et al. (1984) that there is a tighter relationshihp between duration and skewness of saccades than between their amplitude and skewness (see Figs. 4 and 5 respectively).

Third, using the method of Van Opstal et al. (1985) we have reconstructed hypothetical control signals at the motoneuron level for all three experimental paradigms. From the result of our reconstruction (Fig. 6) it is clear that the decrease in peak velocity of remembered targets and anti-saccades is reflected in a decrease of the high-frequency motoneuron burst, while the increase in saccade duration has its counterpart in the prolonged duration of the burst. The fact that there appears to exist a strong coupling between saccade duration

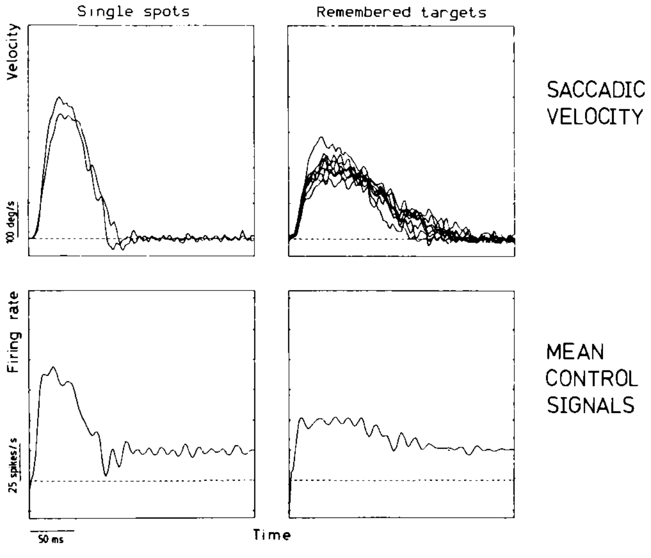

Fig. 7 Velocity profiles (top row) and reconstructed pulse-step signals (bottom row) for subject IMF in two conditions for horizontal 19 deg saccades to the right. N = 2 for the single spot case, and N = 8 for the remembered target case.

and the shape of the velocity profile, which we have found, is intriguing but so far unexplained. If the assumptions underlying the control signal reconstructions are valid, slow saccades are skewed because the motoneuron pulse, when stretched in time, also becomes asymmetric.

In subject IMF, remembered target and anti-saccades, especially for larger amplitudes, have peak velocities that are diminished to such an extent that their time course is almost similar to vergence movements (Bahill and Stark, 1979). It is generally held that vergence movements are caused by a step input to the motoneurons whereas saccades require a pulse-step input. In order to check whether, in this subject, remembered target saccades still had pulse-step inputs at their origin, we have reconstructed the neural control signals for this subject as well. In Fig. 7 it can be seen that only a very weak pulse is present in the reconstructed input signal.

The observation of a change in the pulse-step input to the motoneurons may indicate a different neural origin for remembered target and antisaccades. For the latter, evidence for cortical involvement in the human has been presented recently (Guitton et al., 1985). In the monkey, Hikosaka and Wurtz (1985b) have shown that the substantia nigra is involved in generating saccades to remembered targets. The present study supports the idea that differences in the neural origin of these saccades are reflected by changes in saccade dynamics.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

THE CHARACTERISTIC PEAK VELOCITY - MEAN VELOCITY OF SACCADIC EYE MOVEMENTS IN MAN

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The ratio (K) between mean and peak velocity of saccadic eye movements can be considered as an index of the degree of time-optimization of saccades. It appears roughly constant, slightly dependent on the amplitude, and equal to 0.5-0.6. To understand the mechanisms of the saccadic system which are responsible for the time-optimization of the saccades, a study has been fulfilled on the dependence of this parameter on amplitude, eccentricity and direction of the saccades. The results are compatible with the local-feedback theory and with a detailed anatomo-functional model recently proposed by us.

INTRODUCTION

In order to make saccades as fast as possible, the entire trajectory of a saccade of a given size should be executed at the maximum velocity which is available for that size, according to the gain of the pulse generators. If this were feasible, the velocity patterns of a small saccade and of a large one would be like those in Fig. 1A, and the saccadic trajectories would be pure ramps. The ratio (K) between mean velocity and peak velocity would be equal to 1 in these ideal time-optimal saccades. Because of the 10-20 ms inertial time constant of the ocular plants (the other, longer time constant, which is due to visco-elastic forces, is compensated by the saccadic system using a pulse-step command), saccades cannot have an instantaneous rising to the maximum velocity, nor an instantaneous falling to zero at the end. With these restrictions, the velocity patterns become those of Fig. 1B: the small ideal saccade has a triangular-like pattern with K=.5, and the large one has a trapezoidal-like pattern with K=.8. Real saccades have not such a behaviour. Baloh, Konrad, Sills and Honrubia (1975) reported that the ratio between mean and peak velocity is constant and equal to .6. In a previous study (Bianchi, Inchingolo and Spanio, 1982) we found that K is slightly dependent on the saccade amplitude, with a mean value of about .5. Our largest saccades never had K values as high as .8, and had velocity patterns like those in Fig. 1C. According to these results, it appears that large real saccades are not time-optimized with respect to their maximum available velocity.

The parameter K can be considered as a time-optimization factor of saccades. Then real small and large saccades appear to have about the same degree of time-optimization, since they have about the same K values, although large saccades could be theoretically executed with higher K and thus with higher optimization degrees. If the saccadic duration were preprogrammed, as some models state (Young and Stark, 1963), the bursts of activity driving motoneurons could be programmed with a constant firing rate, in order to produce saccades with high K values. On the contrary, it can be proved that a local-feedback scheme (Zee, Optican, Cook, Robinson and Engel, 1976; Jürgens, Becker and Kornhuber, 1981; van Gisbergen, Robinson and Gielen, 1981), does not easily produce large movements with high K values, even taking into account an active brake, which actually compensates the inertial time constant at the end of the saccade.

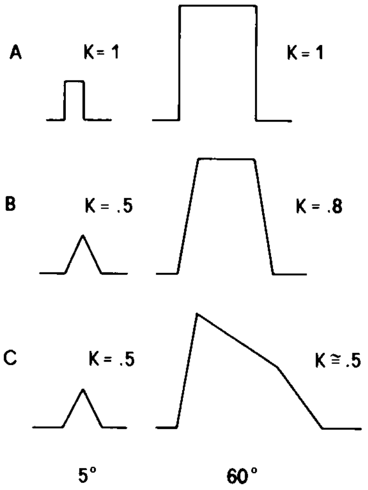

Figure 1
Velocity patterns of a small saccade (5 deg) and a large one (60 deg). A: theoretical, time-optimal saccades wholly executed at the maximum velocity, available for that size. B: theoretical saccades derived from A, by accounting for the inertial time constant of the ocular plant. C: real saccades.

The aim of this paper is to present the results of an extensive study on the K factor, in normal and pathological human subjects, in order to understand the mechanisms of the saccadic system which are responsible for the time-optimization of the saccadic system itself.

METHODS

Experiments were performed by using a microprocessor-based laboratory, described in a previous paper (Accardo and Inchingolo, 1985). Twenty normal subjects, ranging in age from 20 to 38, were examined in dim lighting conditions. Six subjects, aged 29-59, affected by pontine and/or cerebellar pathologies, were also examined. Horizontal saccadic eye movements were elicited through a tracking sequence displayed by the computer on a 255-LED curved screen, kept at a distance of 100 cm from the subject's head. LEDs were switched on in random stepwise jumps of 5-50 deg in both directions, over a visual field of 70 deg. The number of target jumps was limited to 150 to avoid subject fatigue. DC-EOG technique was used in order to collect large and eccentric saccades of the two eyes. The linear range of the measurements from 35 deg to the left, to 35 deg to the right, was checked for every recorded EOG, by plotting a calibration curve of the EOG steady-state positions versus the target positions. Records with non-linear calibration curves were accurately linearized via software, by means of a non-linear compensation, according to the measured calibration curves themselves. As described in previous reports (Inchingolo and Spanio, 1985), the eye movements were low-pass filtered at 50 Hz, by using an analog, 3-pole, Butterworth filter, and then sampled at 500 Hz, 12 bit-digitized and stored on floppy disks. To be able to define the actual eye position, with reference to the primary direction, also the target positions were stored by the computer. The eye movements were then processed off-line and analyzed. An adaptive notch filter was applied to them to reject residual 50 Hz-noise, due to pick-up from the mains. The eye velocity was computed by means of a 2-point derivative algorithm, having a bandwidth of 111 Hz. Saccades were interactively identified by the computer. Their starting and ending times were located by searching the points before and after the identified peak velocity, where the velocity itself reached a preset threshold (10 deg/s). For all the selected saccades, amplitude (A), duration (D), peak velocity (Vp) and rise time to the velocity peak (Tp) were computed. Moreover, the ratio between mean velocity and peak velocity (K), and a parameter representing the asymmetry of the saccades (AS) were also evaluated. The latter parameter was defined as follows:

$$AS = (Tp-D/2)/(D/2) \qquad (1)$$

According to (1) AS=0 represents a symmetrical saccade, having a rise time equal to one half of the saccade duration. On the other hand values lower or greater than zero represent asymmetrical saccades, having rise times shorter or longer than fall times, respectively. For each subject the two main characteristics of saccades, i.e. amplitude-peak velocity and amplitude-duration, were calculated. The amplitude-duration characteristic D(A) was derived by fitting the experimental data as follows:

$$D = D1 \cdot A + D0 \qquad (2)$$

then considering a linear relation between saccadic duration and amplitude, with slope D1 and intercept D0 on the D-axis.
According to previous work of ours (Inchingolo and Spanio, 1985), the amplitude-peak velocity characteristic Vp(A) was derived by fitting the experimental data as follows:

$$Vp = 1/(\alpha + \beta/A) \qquad (3)$$

where Vp saturates for $A \to \infty$ with a value $Vp = 1/\alpha$ and decreases for $A \to 0$ with slope $1/\beta$. We evaluated α and β by fitting A versus the parameter Dp=A/Vp, which we called peak duration, according to the following linear law:

$$Dp = \alpha \cdot A + \beta \qquad (4)$$

from which (3) was derived. Together with the D(A) and Vp(A) (or Dp(A)) characteristics, we analyzed, for each subject, the K(A) and AS(A) characteristics. To be able to study the dependence of the saccadic characteristics on the starting eccentricity and the direction of the eye movements, all the above reported characteristics were evaluated separately for 1) saccades to the right and to the left, 2) saccades of the left and the right eyes, 3) saccades of the adducting and the abducting eyes, and 4) centripetal (or centering) and centrifugal saccades.

As a control of the accuracy of these EOG measurements, we also analyzed saccades (within a +/-10 deg range), recorded from six subjects by using an infrared limbus-tracking device and a 75Hz-bandwidth. The results were largely comparable to those obtained from 50Hz-filtered EOG records. According to a previous study (Inchingolo and Spanio, 1985), the largest EOG errors were found on small saccades: duration and peak-velocity errors were less than +5% and -10%, respectively. K errors were less than +6%. No appreciable errors on AS were found.

EXPERIMENTAL RESULTS

A typical relationship of K versus A is shown in Fig. 2. It appears clearly that K is slightly dependent on A. We modelled the K(A) characteristic as follows:

$$K(A) = \frac{\alpha \cdot A + \beta}{D1 \cdot A + D0} \qquad (5)$$

and we evaluated it from the linear fittings of D(A) and Dp(A), then considering always linear the D(A) and Dp(A) relationships, even when saccades were very slow. Actually, linear D(A) and Dp(A) relationships have been found also in subjects affected by olivopontocerebellar atrophy, who presented very slow saccades (Fig. 3).
A histogram of the distribution of the mean values of K (Km), evaluated, for each subject, from saccades ranged from 5 to 40 deg, is shown in Fig. 4. Km ranged in normal subjects within .47 and .55, with a mean of .513+/-.023. The lowest Km value we found in pathologies of brain-stem or cerebellum was .42. The distribution of the estimated mean values of K for saccades of 5 deg (K5) and of 50 deg (K50) are also reported in Fig. 4. The estimations have been done by applying the model (5) and using the mean values of α, β, D0 and D1 of each subject. The mean values of K5 and K50 on all the normal subjects came to .496+/-.032 and .579+/-.043, respectively. Even if pathological subjects presented saccades with very slow velocities and very long durations, with respect to those of normal subjects, their

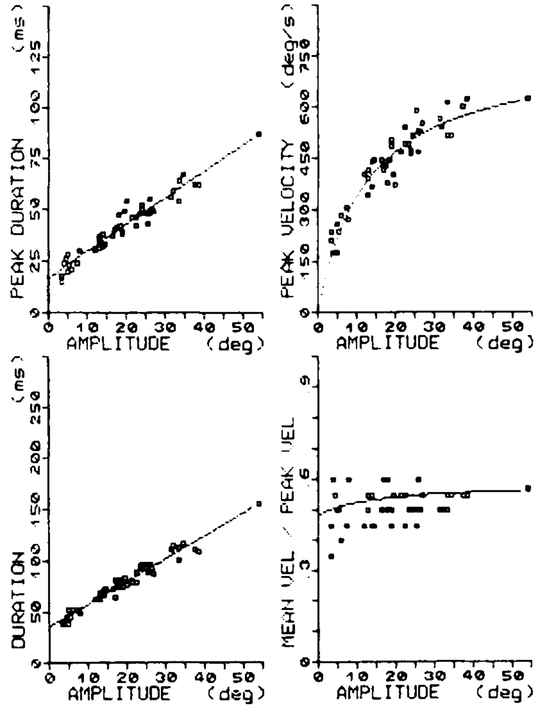

Figure 2
Example of the characteristics D(A), Vp(A), Dp(A) and K(A) in a normal subject. For further explanations see text.

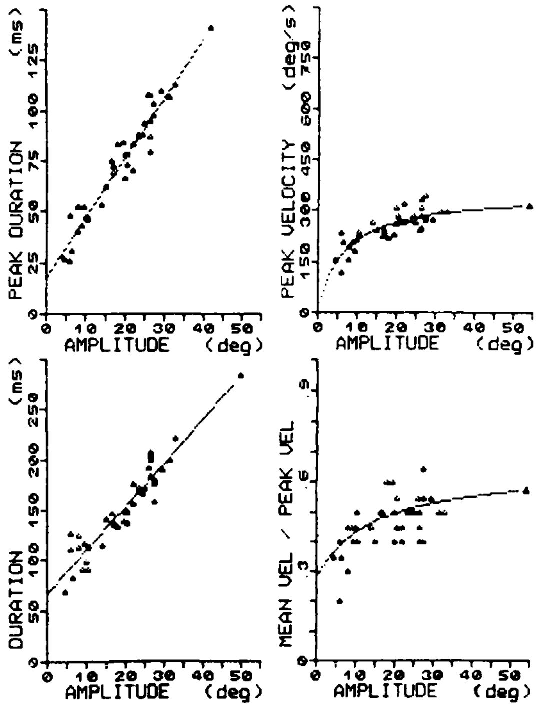

Figure 3
Example of the same characteristics as in Figure 2, in a subject affected by olivopontocerebellar atrophy. K(A) appears slightly lower with respect to that of Figure 2, despite longer durations and lower velocities.

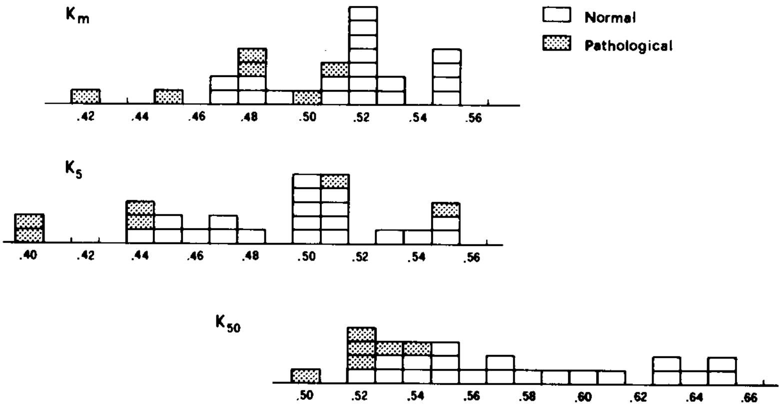

Figure 4
Histograms of Km, K5 and K50 in normal and pathological subjects. Km is the mean K value, averaged over all the saccades ranged from 5 to 40 deg. K5 and K50 are K estimations for saccades of 5 and 50 deg, respectively, obtained by using equation (5).

K50 values were within the normal range, and their K5 and Km values only in some cases were lower than the respective normal ranges.

Fig.5 summarizes the results obtained about the difference between Km of centripetal (Km_{CP}) and centrifugal (Km_{CF}) saccades, and that between Km of adducting (Km_{ADD}) and abducting (Km_{ABD}) ones. In each subject, the difference Km_{CP}-Km_{CF} was very small (Fig. 5), if compared with the large differences of duration or velocity between centrifugal and centripetal saccades (Fig. 6), already reported by Jürgens, Becker and Kornhuber (1981). The inter-individual mean value of the difference Km_{CP} -Km_{CF} was 0+/-.013. The inter-individual mean value of the difference Km_{ADD} - Km_{ABD} was slightly positive, and equal to .016+/-.012. The majority of the subjects had slightly higher Km when adducting (Fig. 5). Fig. 7 shows a typical example of K function for adducting and abducting saccades to the right. Fig. 8 shows the distributions of the absolute values of the differences between Km for rightwards saccades (Km_{RW}) and leftwards ones (Km_{LW}), as well as those of the differences between the saccades of the two eyes (Km_{RE}-Km_{LE}). The inter-individual mean value of $|Km_{RW} - Km_{LW}|$ was .013+/-.011, and that of $|Km_{RE}-Km_{LE}|$ was .010+/-.012. The inter-individual deviations of these differences, as well as those reported in Fig.

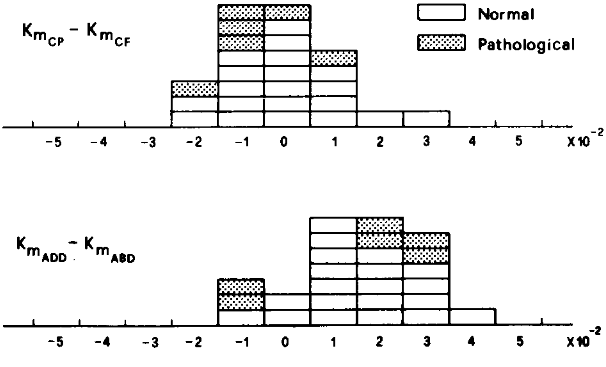

Figure 5
Histograms of the differences between Km values of centripetal (CP) and centrifugal (CF) saccades, and of the differences between Km values of adducting (ADD) and abducting (ABD) saccades, in normal and pathological subjects.

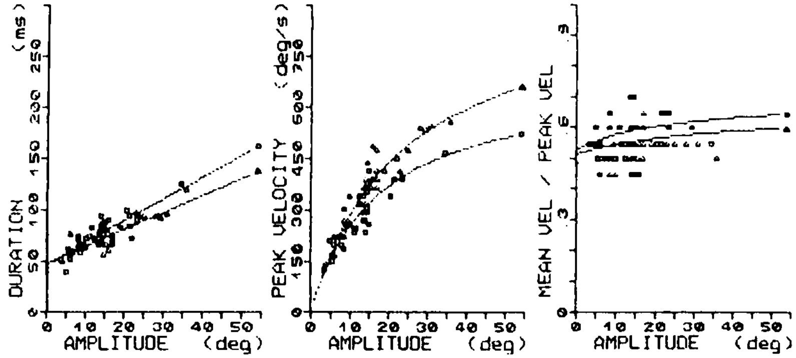

Figure 6
Normal subject. Centripetal (triangles) and centrifugal (squares) saccades present very different values of duration and velocity, but similar K functions.

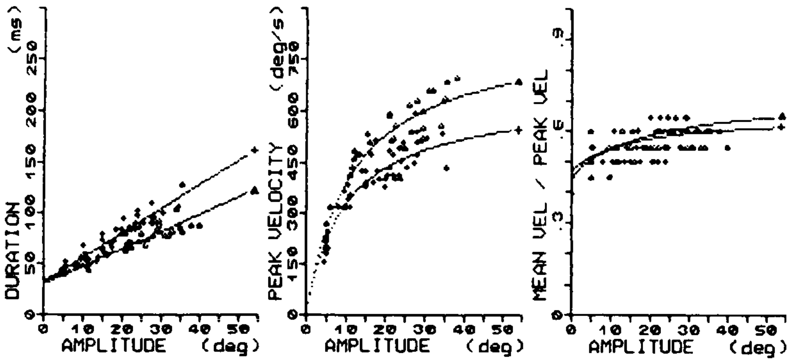

Figure 7
Normal subject. Despite very different values of duration and velocity between adducting (triangles) and abducting (crosses) saccades, the K functions are nearly equal to each other.

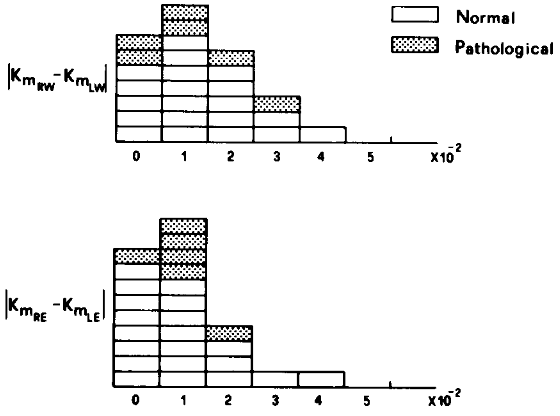

Figure 8
Histograms of the absolute values of the differences between Km evaluated on rightwards (RW) and leftwards (LW) saccades, and of the differences between Km evaluated for the right eye (RE) and the left eye (LE), in normal and pathological subjects.

5, were very small if compared to the inter-individual deviations of Km reported in Fig. 4.

Since saccades having the same K could theoretically have different asymmetries, we also tried to verify if K depended on the saccadic asymmetry or not. We represented analytically the function AS(A) as:

$$AS(A) = \frac{2Tp(A)}{D(A)} - 1 = \frac{2(Tp0+Tp1\cdot A)}{D0+D1\cdot A} - 1 \qquad (6)$$

where Tp0 and Tp1 are respectively the intercept and the slope of the linear regression line between Tp and A. We actually verified that a linear fitting was quite adequate for Tp(A) up to about 30-40 deg. We found very large inter-individual and intra-individual variability of AS(A). But, except for heavy pathologies, like that of the subject of Fig. 3, who exhibited very low asymmetries, no significant variations of K(A) corresponded to variations of AS(A). In Fig. 9, for example, the abducting saccades were more asymmetric than the adducting ones, but the characteristics K(A) were about the same for both. The difference between the two asymmetry functions was due, in that example, to a slightly higher rise time in abduction than in adduction. K functions were equal in the two cases, since abducting saccades presented longer durations but proportionally lower peak velocities, with respect to adducting ones. Inter-individual differences of saccadic asymmetries were often due to large differences in the durations. However, the duration differences were compensated by differences of opposite sign in the peak velocities, thus giving similar values of K.

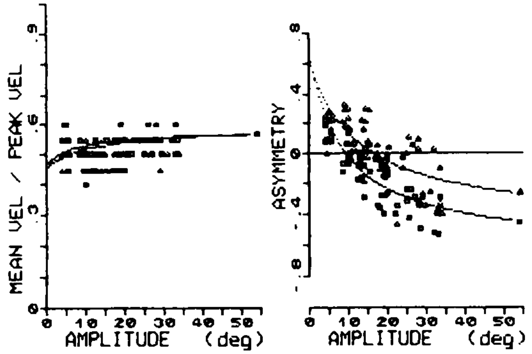

Figure 9
Normal subject. The K fuctions of adducting (triangles) and abducting (squares) saccades are very close to each other, whereas the corresponding asymmetries are different. For further explanations see text.

DISCUSSION

Our experimental results show that the time-optimization factor K of saccadic eye movements is roughly constant in each subject, and it is not dependent on the actual asymmetry of saccades with the exception of very slow saccades. This is due to the fact that long saccadic durations are balanced by low peak velocities, in such a way that their product is always rather constant, for a given amplitude, and equal to about twice the amplitude itself (K=.5). The constancy of this product, for a given size, has been also reported by Evinger, Kaneko and Fuchs (1981) for man, monkey, cat and rabbit. From the neurological point of view, this constancy can be ascribed to a constancy, for a given saccadic size, of the product between maximum firing rate and duration of medium lead burst neurons (pulse generators). Furthermore, the product should be equal to about twice the number of spikes of the bursts. Indeed, Bon, Corazza and Inchingolo (1980) found in the cat a linear relation with slope 0.5 between mean and peak firing rates of pretectal NTO burst neurons, which have been proved to be efference copies of the pontine burst neurons (Bon, Corazza and Inchingolo, 1984). Furthermore, burst neurons of the pontomedullary reticular formation, recorded by van Gisbergen et al. (1981), exhibited pseudo-triangular shapes, like those reported in Fig. 1C (with the exception, in the former, for the lower rising and falling times), indicating a ratio of about .5 between mean and peak firing rates. This behaviour can be simply explained if we assume the existence of a bilateral local-feedback circuitry, where burst neurons are fed by motor errors (that progressively decay) and whose outputs are then integrated to give step commands to motoneurons. The neurophysiological hypothesis that burst discharge results from both a velocity and a duration input (King and Fuchs, 1977; 1979), seems not adequate, since the brain would then be able to better program both duration and velocity, in order to produce large saccades with high K values, and therefore with a high degree of time-optimization.

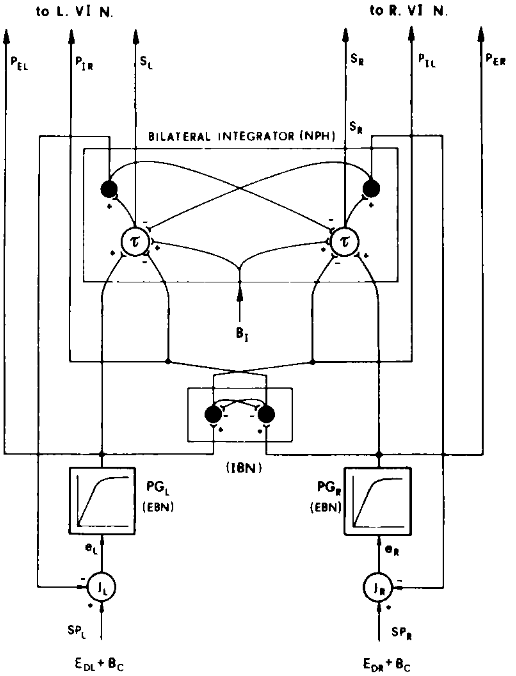

Figure 10
Model of the horizontal bilateral premotor circuit generating pulse (P) and step (S) commands to the ocular motoneurons (L.VI N., R.VI N.).
E_{DR} and E_{DL}: desired eye innervations. B_C and B_I: biases. e_R and e_L : motor errors. PG_R and PG_L : pulse generators.

By simulating the saccadic system by means of the bilateral local-feedback model reported in Fig 10 (Inchingolo, 1985), we obtained families of saccades having K functions slightly dependent on amplitude, in agreement with our experimental results. The inter-individual differences, found by us on Km, can indicate a slightly different degree of time-optimization among subjects. These differences have been simulated by this model, varying some parameters which can affect the degree of active-braking (Sindermann, Geiselmann and Fischler, 1978), i.e. of multipulse control (Lehman and Stark, 1983), like, for example, the bias B_C at the inputs or the IBN-IBN gains. In such a way, only saccadic durations were changed, but peak velocities did not. So we can explain why two subjects, having the same Vp(A) characteristic, can have slightly different D(A) characteristics, and therefore slightly different values of K. On the other hand, two subjects can have equal values of K, i.e. equal degrees of saccadic time-optimization, even if their peak velocities are different, as well as their durations. It is sufficient, as we experimentally verified, that the Vp(A) and D(A) characteristics balance each other, i.e. that the values $\beta/D0=K(0)$ are equal in the two cases, as well as the values $\alpha/D1=K(\infty)$.This behaviour has been simulated by the model of Fig. 10, by varying the gains and the saturation levels of the pulse generators. Moreover, when we simulated the system with very low values of the pulse generator parameters, a general decrease of K, mainly for small saccades, was obtained. This is in agreement with some our experimental results on patients, like those reported in Fig. 3.

We found very modest differences of Km between saccades of the two eyes, or between leftwards and rightwards saccades: the former can be ascribed to small differences in the dynamics of the two sets of motoneuronal pools and, moreover, of the ocular plants. The latter can be also due to slight differences between the two sides of the bilateral premotor circuit, modelled in Fig. 10.

The very modest differences of Km we found between abducting and adducting saccades cannot be ascribed to different controls to lateral rectus of one eye and medial rectus of the other eye, as Vilis, Snow and Hore (1983) proposed. Rather, they can be ascribed to a slightly different dynamics of the ocular plants in the two conditions, due to the known anatomo-functional differences between medial and lateral recti.

We found that centrifugal and centripetal saccades had the same inter-subject Km mean value. This finding suggests that centrifugal and centripetal saccades are generated by the same neural circuitry, even if some parameters in the circuits should have different values in the two cases. It can be proved that centrifugal saccades should be executed with longer durations than the centripetal ones (and they are actually so), to produce the correct pulse-step matching, because motor fibers of both agonist and antagonist muscles work in a non-linear region to produce them. Flocculus can control the correct pulse-step matching for centrifugal saccades, by decreasing the gain of the central integrator. In such a way, the durations of centrifugal saccades are longer than those of centripetal ones but, at the same time, their peak velocities are lower; as a consequence, centripetal and centrifugal saccades have about the same K.

CONCLUSIONS

The mean velocity-peak velocity characteristic K(A) of saccadic eye movements can be considered as a property of the nervous circuitry which generates the innervational commands to the extraocular muscles, in order to produce saccades. The bilateral local-feedback loop hypothesis seems to be adequate to fully explain the experimental values of K(A) found both in normal and pathological subjects. This characteristic can be effectively used as an index of the degree of time-optimization of the saccadic system.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

STIMULUS-INDUCED MIDFLIGHT MODIFICATION OF SACCADE TRAJECTORIES

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Eye movement responses of human subjects were recorded in response to two-dimensional double-step stimuli. When the first step was large (40 deg), responses with spectacular curvature in the direction of stimulus movement were often observed. The amount of curvature, its onset relative to the second step and its relation to the vectorial velocity profile were analyzed quantitatively. The data are discussed against the background of two different models.

INTRODUCTION

In this paper we reexamine saccade trajectories in response to two-dimensional double-step stimuli where the target suddenly changes its direction of movement. It would be expected from Robinson's internal feedback model (Robinson, 1975; Van Gisbergen, Robinson and Gielen, 1981) that the saccade under these experimental conditions may show a trajectory which is curved in the direction of stimulus movement. Several groups have performed this type of experiment in humans, cats and monkeys, but taken together, the results have so far been inconclusive. First, the predicted curved saccade trajectories were regularly found in the monkey (Van Gisbergen, Ottes and Eggermont, 1982), when large stimulus displacements of up to 45 deg were used, and have also been noticed in experiments on cats (Evinger and Fuchs, 1978). On the other hand, curved saccade responses were not (Hou and Fender, 1979; Lisberger, Fuchs, King and Evinger, 1975), or only very rarely (Findlay and Harris, 1984), observed in studies on humans. In these studies stimuli were not presented beyond 8 deg eccentricity. Second, there is no agreement in the literature on how to interpret curved trajectories when they are found. In terms of Robinson's model the curved trajectory is interpreted as a single saccade which is terminated as soon as the internal representations of eye position and target position match. According to this model, saccades are not preprogrammed but can respond to new target information which becomes available even after the movement has started. A different interpretation of curved saccade trajectories in response to two-dimensional double steps was proposed by Evinger and Fuchs (1978). They suggested that the addition of two temporally overlapping saccades may cause the hooked trajectory.In the present paper, this interpretation will be referred to as the two-saccade hypothesis.

Our data show, for the first time, that spectacularly curved saccades can be readily elicited also in humans, but only in response to large stimulus displacements. With down-scaled stimuli the phenomena become more subtle.

METHODS

Experiments were conducted on three human subjects who faced a screen at 57 cm in front of them with a background illumination level of 1.2 cd/m^2. Vision was binocular. Subjects were instructed to refixate the target, after it jumped, as quickly and as accurately as possible. The head was stabilized with a bite board and a head rest. Eye movements of the left eye were recorded with the double magnetic induction method described by Bour, Van Gisbergen, Bruijns and Ottes (1984). The horizontal and vertical raw eye position signals were low-pass filtered (-3 dB at 150 Hz), sampled at a rate of 500 Hz in each channel, and stored on disk. The data were corrected for the static non-linearity inherent in the recording method (for details, see Bour et al., 1984). All three subjects, one of whom was naive, had qualitatively similar responses. A full quantitative analysis was carried out in two subjects (JR and JVG).

In single-step trials, subjects were required to refixate the 2 deg circular target (5 cd/m^2) after it jumped from the initial fixation position (F) at 20 deg on the left of the primary position, through an angle of 40 deg to a new position in the upper (ϕ = 22.5 deg) or lower (ϕ = -22.5 deg) part of the right half field (see Fig. 1). In clockwise double step trials the target jumped first to the up location, where it remained during a time (τ) of 50, 70 or 90 msec, followed after a dark period of 20 msec by a second vertical step to the down position. In anticlockwise trials the double step was in the opposite direction (Fig. 1).

Randomly interspersed with the other trial types, single steps to locations at different eccentricities and along other meridians were also presented. In all trials the stimulus remained at the final position for at least 900 msec. The time (Δ) between fixation spot offset and stimulus onset at the first peripheral stimulus location was varied, in different experimental runs, from

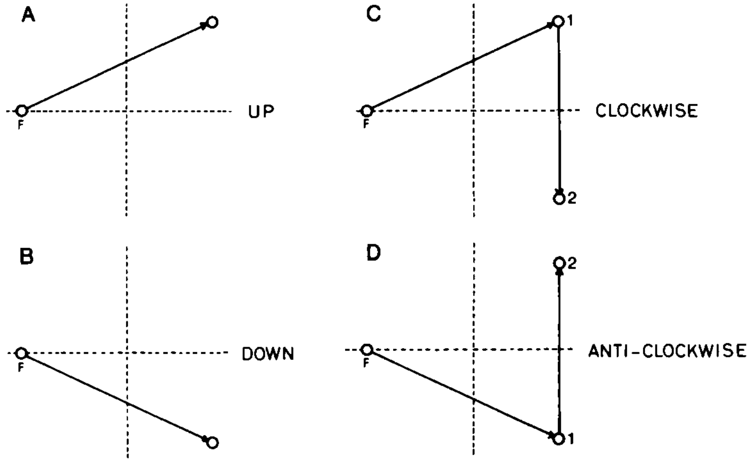

Figure 1
Control stimuli (A and B) and double step stimuli (C and D) used in the experiments. The fixation point (F) was on the left-hand side of the primary position, indicated by the dotted lines.

-50 msec (overlap condition), through 0 msec to +50 msec (gap condition). The various combinations of τ and Δ yielded responses over a wide range of onset latencies relative to the onset of the second step in double step trials. Data presented in the Results were obtained by pooling across τ and Δ, unless noted otherwise.

In a second series of experiments, the double step stimuli and the single step controls were scaled down in size by a factor of two. In these experiments F was at 10 deg to the left of the primary position and the first step was 20 deg along the same meridians. In both the 40 deg and the 20 deg experiments a total stimulus sequence consisted of 80 trials. Of these, 15 were clockwise double steps, 15 were in the opposite direction; the other stimuli were all single steps and included 10 control trials to both the up and the down position (see Fig. 1).

RESULTS

The 40 deg double step experiments yielded numerous examples of saccadic responses with obvious stimulus-induced curvature in all three subjects. To illustrate this with an example, Fig. 2 shows all double step and control single step responses obtained from one subject in a single stimulus sequence (Δ = 50 msec; τ = 50 msec). The single step control responses (upper panels) had only a modest degree of curvature. By contrast, the curvature in double step responses may be quite spectacular. In many of these strongly curved saccades the eye moves initially in the direction of the first target position but then changes direction and ends up, ultimately, near the final target position. This leads to opposite directions of saccade curvature for the two types of double steps (lower panels in Fig. 2). The fact that the sign of saccade curvature can be changed by reversing the direction of the double step stimulus, taken together with our observation that the single step responses are more nearly straight, demonstrates that the strongly curved saccades were really caused by the second stimulus step.

It should be noted that not all double step responses were strongly curved in the direction of stimulus movement. First, there were responses consisting of a nearly straight saccade to the first stimulus position. These were followed, after a short fixation, by a second vertical saccade to the final stimulus position. Several examples can be observed in Fig. 2. Second, there were responses which ignored the first stimulus position and brought the eye directly near the final stimulus position. These responses, typically with a long onset latency after the second stimulus step, may be as nearly straight as corresponding single step control responses. Saccades heading toward the first stimulus position typically had short latencies relative to the second step. In between these extremes there is a latency range where the strongly curved responses ocurred.

We have discovered that there exist interesting relations between the initial direction of a saccadic response and the sign and the degree of curvature in its overall trajectory. To study these relations quantitatively, we have defined three quantitative measures to characterize each trajectory [cf. Findlay and Harris (1984)]: Overall direction (ϕ_o) was defined as the direction of a straight line connecting onset and offset of a saccade. Initial direction (ϕ_i)was defined as the direction of a straight line through saccade onset and the eye position reached 20 msec later. Curvature (C) was defined as the direction difference between initial and overall saccade direction ($C = \phi_i - \phi_o$). These measures are illustrated schematically in Fig. 3.

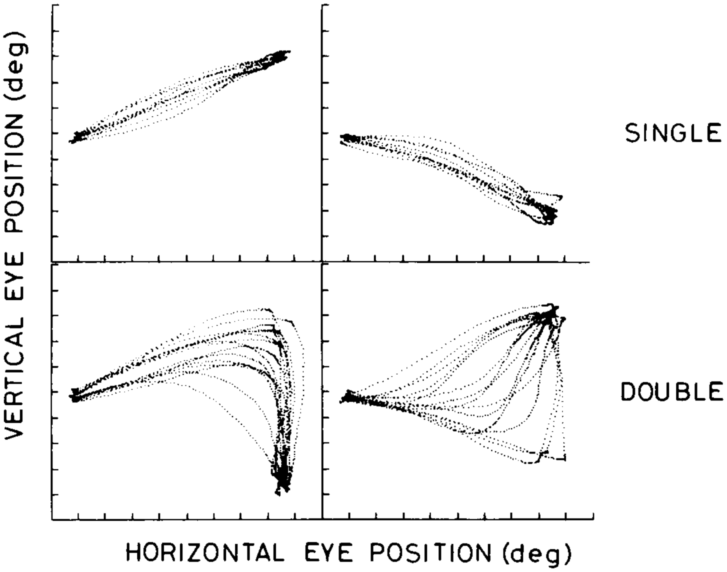

Figure 2
Responses of subject JR to large single steps and double steps. Total range of horizontal and vertical axis in each box is 50 deg (each division 5 deg). Fixation point prior to the movement is on the left. Left-hand column: responses to up single steps and clockwise double steps. Right-hand column: responses to down steps and anticlockwise double steps. See also Fig. 1.

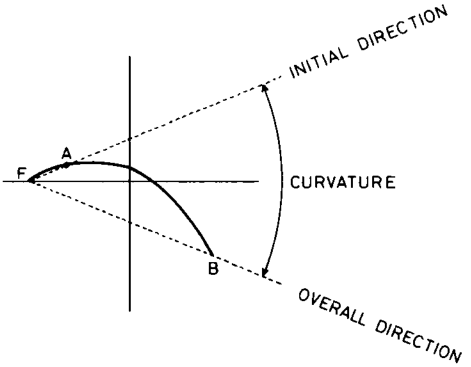

Figure 3
Schematic illustration to define initial direction, overall direction and curvature of a curved eye movement starting in F and moving to B through point A at a time 20 msec after onset.

We will first discuss the properties of single-step control responses.It was noticed that these saccades show considerable scatter in their initial directions but have more precise overall directions. The reason behind this phenomenon is that the degree of curvature and initial direction are rather tightly related. This is obvious from the plots in Fig. 4 where a strong linear relationship between these two saccade parameters emerges for each of the two control steps in the two subjects investigated quantitatively. We have characterized the entire ensemble of single step responses by the linear relation: $C = a(\phi_i - b)$ where a is a constant determining the slope of the linear relation; b is the intercept on the horizontal axis and depends on target direction (Fig. 4). The symbols C and ϕ_i have been defined earlier. Ideally, if all responses would be goal directed despite the observed scatter in initial directions, constant a should be 1.0 and b should be 22.5 deg or -22.5 deg for up and down steps, respectively. The actual values for two subjects investigated on this point are summarized in Table 1. Note that, since slopes are less than 1.0 , curvature in the saccade does not completely compensate for initial direction errors.

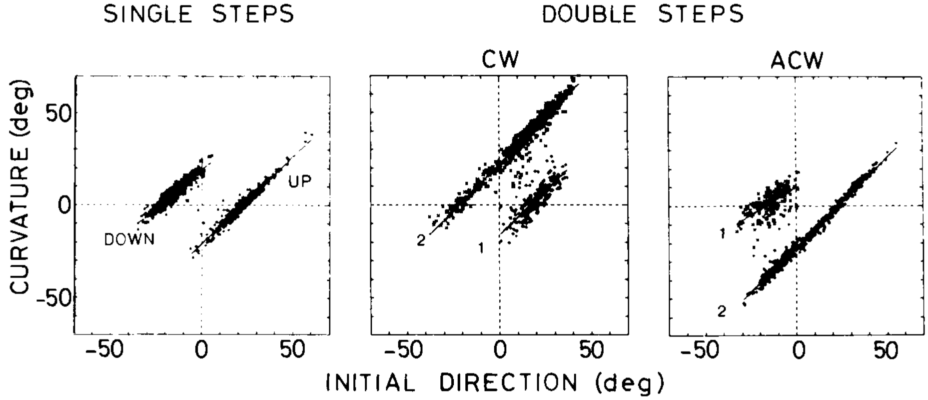

Figure 4
Relation between curvature and initial direction of responses from subject JR. Left-hand box: responses to up and down steps shown in Fig. 1. Middle box: responses to clockwise double steps. Right-hand box: anticlockwise double step results. Large stimulus displacements. The straight lines through the data points are linear regression lines. The separation boundary was taken as the 45 deg line through the origin. The linear relation is significant in all cases.

Table 1. Slope (a) and horizontal intercept (b) of curvature/initial direction relation for single step control responses (40 deg). Number of saccades: N; correlation coefficient: r. In all cases the relation is significant at the $P < 0.001$ level.

stimulus	subject	a	b	r	N
up	JR	0.94	22.5	0.97	446
	JVG	0.79	22.0	0.86	550
down	JR	0.83	-23.1	0.92	446
	JVG	0.63	-24.6	0.77	550

A similar significant relation was also found in a much smaller sample of 20 deg control responses in both subjects investigated. Slopes were still more clearly below 1.0, indicating that curvature was typically insufficient to compensate fully for an offset in the on direction of the saccade. In both subjects initial directions of 20 deg saccades varied over a more narrow range and were more nearly equal to target direction than in the 40 deg control responses. The 20 deg control responses were also more nearly straight.

The responses to double steps can best be described by comparing them with the single step control responses. Curvature/initial direction plots constructed from pooled 40 deg double step data show two distinct, almost entirely separate clusters of data points (Fig. 4). Of course, if the double-step stimuli were only to elicit saccades either to the first or to the second stimulus position, one would simply observe a combination of the two single step clusters shown in Fig. 4 (left-hand box). These responses were indeed observed but, in addition, it can be seen that many of the clockwise double step responses with final directions corresponding with the final target position (down; cluster 2) have extreme positive curvature never observed in the control trials. These data points come from responses which were initially directed near the first stimulus position (up) but then changed course and moved all the way to the second target position (down). As we remarked before, part of the responses in cluster 2 have the same properties as single spot control responses to the down position.

Similar relations hold also for the anticlockwise double step results. In these data the saccades with extremely large negative (anticlockwise) curvature are clearly distinct from the single-step control results (see right-hand box in Fig. 4). Again, cluster 1 contains responses to the first step which are not as precise as the single step responses. This reduced precision, and the slight direction bias toward the second stimulus position, may be due to the short presentation time of the spot at the first target position and its subsequent reappearance at the second position.

Similar analyses were also performed on 20 deg double step experiments. The evidence for stimulus-induced saccade curvature in these experiments is much less spectacular. Yet, comparison of single and double step data (Fig. 5) suggests that also the down-scaled double steps lead to stronger saccade curvature in the appropriate direction.

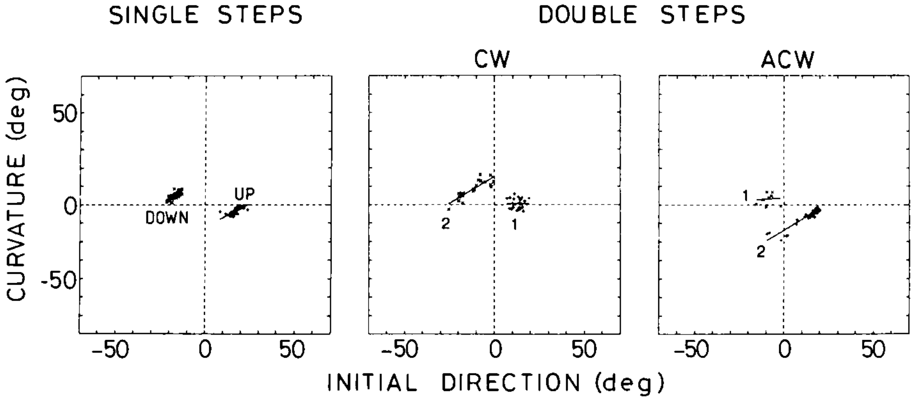

Figure 5
Same relations as in Fig. 4 for responses from subject JVG obtained in 20 deg experiments.

DISCUSSION

Midflight modification of saccade trajectories by two-dimensional double stimuli, a possibility suggested by the internal feedback model (see Introduction) was clearly demonstrated in our experiments with large stimulus displacements. Since these effects were less immediately obvious when smaller stimulus displacements were used, the failure to observe these phenomena in earlier reports is probably related to the use of much smaller stimulus amplitudes in these studies.

It is interesting to see that an important prediction from Robinson's model was confirmed under certain experimental conditions but, to view the results in a broader perspective, it is essential to consider alternative models. We have explored the explanatory power of the two-saccade hypothesis mentioned in the Introduction. For this purpose, we selected responses from anticlockwise double step trials which were initially aimed at the first stimulus location (down) but then changed course and brought the eye in a single uninterrupted movement to the final target position (up). There are also trials where these responses to the first stimulus consist of two separate saccades in response to the two stimulus steps. To explain the strongly curved trajectories observed, it may be argued that the second (vertical) saccade may start before the first saccade was completed. In an attempt to determine when this hypothetical second saccade began, we have timed the moment of curvature onset in a number of strongly curved trajectories with initial directions to the down position. This moment was taken as the time when the vertical eye velocity signal reversed sign. The histogram summarizing these reconstructed 'second saccade onsets' is shown in Fig. 6. It appears that the first curvature onsets appeared some 120 msec after the second step began. Second saccade onsets in trials which led to two separate, roughly straight saccades started somewhat later (middle box in Fig. 6). The sum of the two histograms (bottom) resembles a normal saccade latency histogram so that these data are at least compatible with the two-saccade explanation.

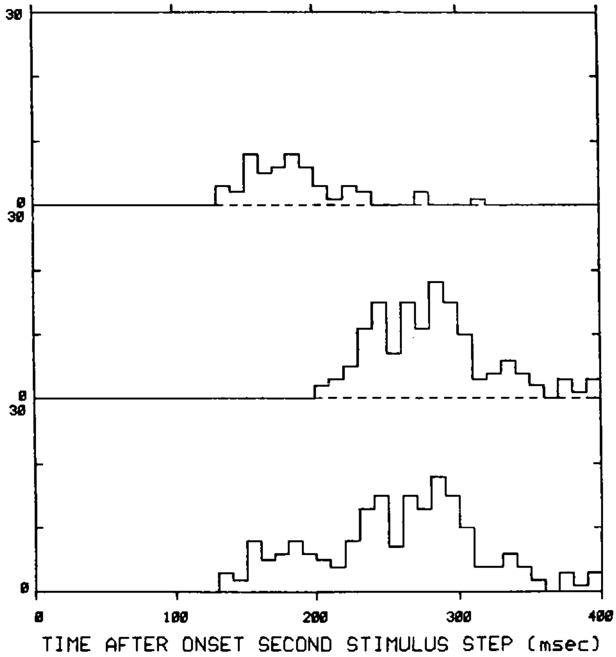

Figure 6
Reconstruction of second saccade onsets based on two-saccade hypothesis. Upper box: moments when upward curvature starts in strongly curved responses to anticlockwise double steps (40 deg). Middle box: onset of second saccade in trials where first saccade brought the eye to the first stimulus location. Lower box: combination of two upper histograms. Data from subject JVG; $\tau = 90$ msec; pooled from separate $\Delta = -50$, 0 and 50 msec experiments.

The two-saccade hypothesis has also invited us to look at velocity profiles of responses with strong curvature. If these consist of two overlapping saccades, one might expect to see double peaked vectorial velocity profiles, at least in some cases. Such velocity profiles were indeed regularly observed in responses with an abrupt change in direction (Fig. 7). The first column in Fig. 7 shows a response consisting of two temporally isolated saccades: one to the first followed by a second to the final target position. The second and third column display responses with strong curvature where the eye does not stop. As the vectorial velocity profiles (lower boxes) show, the eye slows down temporarily. These dips coincide approximately with the point of maximum curvature, in the mathematical sense, in the trajectory.

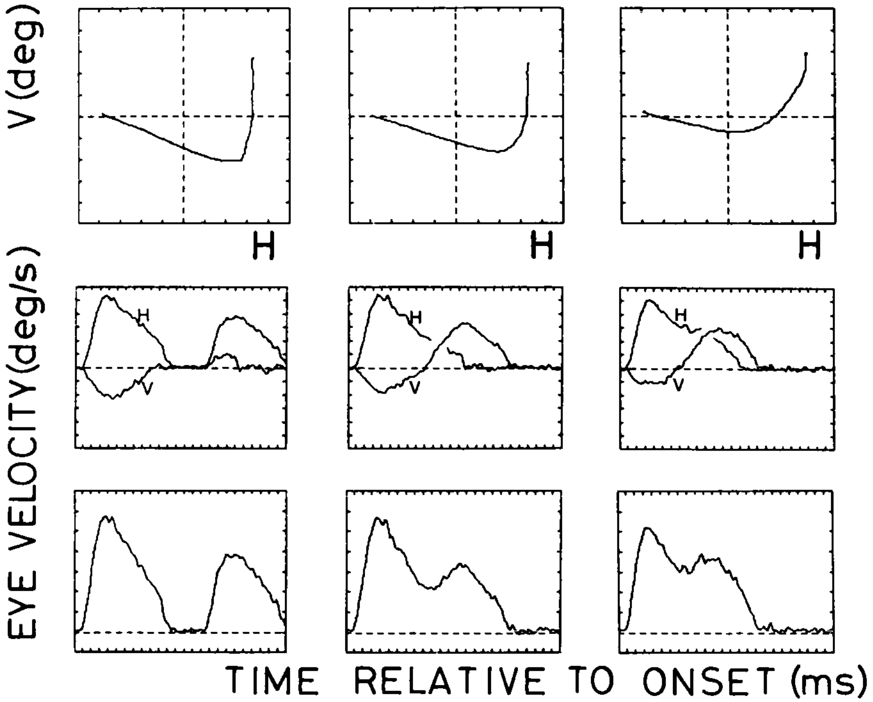

Figure 7
Three examples of responses obtained in large anticlockwise double-step experiments. Subject JVG. Upper row: trajectory in HV plane. Scale: 5 deg per division. Middle row: horizontal and vertical component velocity. Lower row: vectorial eye velocity. Scales in middle and lower row: 100 deg/sec per division (vertical axis); 10 msec per division (horizontal axis). Note that curved responses in middle and right column show dip in vectorial eye velocity profile. This dip occurs approximately at the time when vertical eye velocity reverses sign (curvature onset).

These preliminary ideas on possible underlying mechanisms suggest a possible explanation of why strongly curved double step responses were regularly observed only in a restricted latency range relative to the second step and were most common for large stimulus displacements. One reason may simply be that the probability of the effect of the second step interfering with the response initiated by the first is maximal if the second step has just the right timing and if the response to the first step has a long duration.

The data in this report support the internal feedback model in that the prediction of curved trajectories in two-dimensional double-step responses was confirmed. There is a hint that similar mechanisms may also be at work during the execution of single step saccades. On the other hand, we have shown that the onset of the curvature induced by the second step is highly variable. This means that there is not a simple direct link between the visual stimulus and the motor response which could be modelled adequately by a fixed delay. It seems rather more likely from our data that the processing stages which are responsible for the stochastic nature of saccade initiation in response to a simple step are again at work in preparing responses to a second step. To account for these findings, the fixed time delay for 'visual signal processing' in the internal feedback model will have to be modified. It is conceivable that a combination of the original Robinson model with the two saccade hypothesis would serve this purpose. Such a combined model, which remains to be precisely specified, may also solve the problem inherent in the two saccade hypothesis that somehow the effect of the first saccade must be taken into account when executing the second if the eye is to be on target (Evinger and Fuchs, 1978).

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EYE MOVEMENTS: From Physiology to Cognition
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THE ROLE OF ATTENTION IN THE PREPARATION OF VISUALLY GUIDED SACCADIC EYE MOVEMENTS IN MAN

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The reaction times of visually guided saccades (SRT) were analyzed in different conditions. Very short saccadic reaction times (express saccades) of 100-130 ms measured from the appearance of the target were obtained, if a spot of light, which the subject had to attend to, disappeared 200 ms before the saccade target appeared. Whether the attention target was presented foveally (thereby serving as a fixation point) or peripherally made little difference. Virtually only long SRT were observed in the presence of directed visual attention at the moment of target appearance. We conclude that directed (engaged) visual attention inhibits the execution of saccades and must be interrupted (disengaged) before a saccade can be made.

INTRODUCTION

It is well known from studies in animals and humans that reaction times of goal directed saccadic eye movements are largely dependent on the experimental conditions used. In 1967 Saslow showed in man that the introduction of a temporal gap between the disappearance of the fixation point and the appearance of the saccade target (gap condition) decreases the saccadic reaction time (measured from the appearance of the target) from about 220 to about 140 ms. Using the gap condition, the existence of a group of saccades with even shorter reaction times (express saccades) on the order of 70 ms in monkeys and 100 ms in human subjects, has been demonstrated (Fischer and Boch, 1983; Fischer and Ramsperger, 1984). In the gap condition, the distribution of saccadic reaction time of most human subjects is bimodal with one peak of express saccades between 100 and 140 ms and another peak between 150 and 200 ms ("fast regular saccades"). Using the overlap condition in which the fixation point remains visible until the saccade target appears, the distribution of most human subjects is unimodal with a broad peak around 250 ms ("slow regular saccades") and only very few saccades with reaction times below 200 ms. These results indicate that the visual to oculomotor system involved in programming and execution of a goal directed saccade can occupy different internal states at the moment in which the target appears. It is supposed that the different populations of saccadic reaction times reflect these different internal states, which can be manipulated by the experimental conditions and - may be - by the instructions to the subjects. It was assumed in the beginning that the disappearance of the fixation point was necessary to enable the visual to oculomotor system to initiate express saccades. However, later observations showed that monkeys as well as human subjects eventually could execute express saccades also in the overlap condition (Boch and Fischer, 1986; Fischer and Ramsperger, 1986). We therefore wondered, what really the necessary and/or sufficient conditions are, under which express saccades are obtained. Here we report the results of several experiments designed to investigate further the differential influence of fixation versus visual attention on the reaction time of goal directed saccades (Mayfrank, Mobashery, Kimmig, and Fischer, 1986). More details about the conditions under which express saccades occur and the intrasubject variability have been investigated by Mobashery (1986).

METHODS

Apparatus: Horizontal eye movements were recorded using an infrared light technique (Gauthier and Volle, 1975) detecting saccades of 0.25 deg in size. Eye position was displayed on a storage oscilloscope. Artifiacts, like blinks and eye movements not directed to the visual target, were eliminated immediately. Saccadic reaction times were determined automatically by an electronic threshold detector. Histograms of saccadic reaction times were displayed on line on a computer terminal screen using a bin width of 10 ms. The number of express saccades in a given distribution was determined by counting the number of saccades with reaction times between 85 ms and the first dip in the distribution occurring usually around 130-150 ms.

Subjects were placed 67 cm in front of a translucent screen with their head stabilized by a chin rest. Visual stimuli were projected onto the screen by light emitting diodes.

In all experiments the subjects had to first keep their eyes fixed straight ahead on the center of the screen at which a bright fixation point was presented in one part of the experiments. In most experiments the visual target for the saccade appeared in random order at 4 deg to the right or left from the center of the screen. In 2 experiments the target appeared always at 4 deg to the right. The task was to make a saccade as quickly as possible to the visual target. The saccadic reaction time was measured from the onset of the visual target to the beginning of the saccade.

Two main paradigms were used throughout: (a) Gap condition (see fig. 1, upper part): The central fixation point appeared and remained on for 2 sec and the target appeared 200 ms after the fixation point had been turned off. In one experiment, however, we systematically changed the gap duration (see results); (b) Overlap condition (fig. 1, lower part): The fixation point remained visible while the target appeared. The target appeared always 2 sec after fixation point appearance. In the gap condition, even if subjects could predict the time of target appearance, almost no anticipatory saccades were made if the localization of the target was randomized between right and left. If, however, the target position was kept constant most subjects produced an appreciable number of anticipatory saccades (up to 50%). These could be identified on the basis of their rather short latency ($<$ 70 ms) as well as on their hypometric amplitude. Four subjects were run in a slightly different version of the gap and overlap condition: they were instructed to keep their eyes fixed on the center of the screen while paying attention to a light spot placed 5 deg up the vertical meridian before target appearance, thus dissociating their direction of gaze from the direction of visual attention. The peripheral attention target was turned off or not as described above (gap and overlap condition). For four subjects no light spot was visible before target presentation: in a first experiment

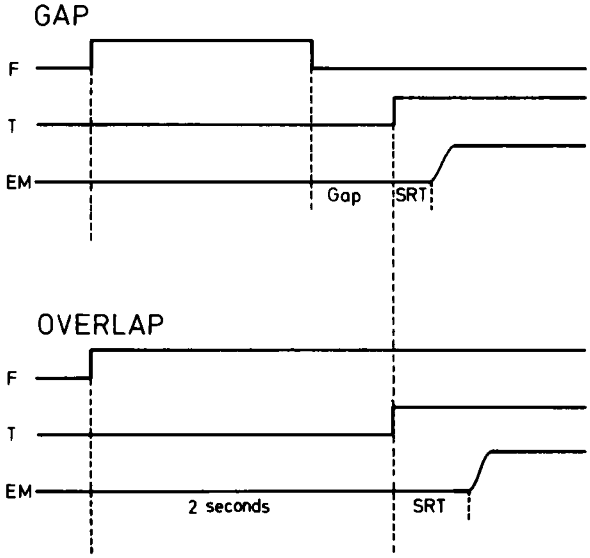

Fig. 1: Time course of the two experimental conditions used. Gap: the fixation point (F) disappears some time (gap) before the target (T) for the saccade appears. Overlap: the fixation point remains visible while the target appears. EM - eye movement, SRT - saccadic reaction time.

they had to make a saccade to a target suddenly appearing in total darkness, in a second experiment subjects' direction of gaze and visual attention was defined by the middle of an incomplete cross. More details are described in the appropriate section of the results.

To eliminate effects of training, control measurements were always made during the same session. From each subject 100 or 200 saccades were collected for each experimental condition.

RESULTS

The pooled histograms of 4 naive subjects in the ordinary gap condition (central fixation point disappearing 200 ms before target onset) and the overlap condition (central fixation point remaining visible while the target appears) are shown in fig. 2A. The targets appeared in random order 4 deg to the right or left of the central fixation point. Fig. 2A, left part, shows the typical bimodal distribution in the gap condition with a distinct subpopulation of express saccades (first peak) and a second peak of "fast regular" saccades. In the overlap condition (fig. 2A, right part) the distribution of saccadic reaction times is unimodal with a broad peak around 250 ms and shows only few saccadic reaction times below 200 ms and virtually no express saccades.

One might conclude from these data that express saccades are produced in the absence of foveal fixation at the moment where the target appears. To test this hypothesis, the same 4 subjects were run in two experiments in which no foveal fixated light point was present before target onset. First, subjects had to look attentively at the middle of an incomplete cross on the screen to give them an imaginary fixation point, second, they were instructed to look straight ahead in total darkness before target appearance. In both conditions almost no express saccades were obtained. In fact, these distributions are hardly different from the histogram in fig. 2A, right part. In conclusion, the absence of a physical fixation point before target onset is not a sufficient condition for the occurrence of express saccades. Therefore we assumed that directed visual attention before target onset (as being present in the overlap condition and the incomplete cross task) might prevent the oculomotor system from producing express saccades.

In order to differentiate between the effects of foveal fixation and visual attention we dissociated the direction of gaze from the direction of visual attention: 5 subjects were run in the overlap and gap condition, with the instruction to keep their direction of gaze in the middle of the screen while paying attention to a light spot placed (a) 5 deg up the vertical meridian and (b) 4 deg to the right (at the position where the saccade target would occur) before appearance of the target for the saccade.

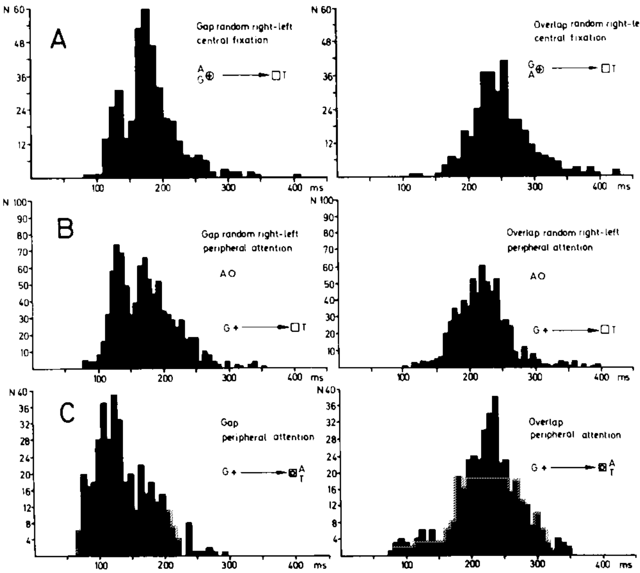

Fig. 2 A-C: Distributions of saccadic reaction times with central (A) and peripheral (B,C) visual attention. The circle marks the position of the attention cue, the cross marks the direction of gaze, the square indicates the target position. In the left part of A,B,C the gap condition was used, respectively, in the right part the overlap condition. Note the similarity of the gap situations and the similarity of the overlap situations and the dissimilarity between the corresponding gap and overlap conditions.

Fig. 2B,C shows the results. The insets beside the histograms indicate the direction of gaze (G = center of the screen), location of the "attention target" (A), and the position where the target for the saccade would appear (T). In fig. 2B saccade target location was randomized between 4 deg to the right and left. In fig. 2C the saccade target appeared always 4 deg to the right. If the attention target disappeared 200 ms before saccade target onset (gap situation), many express saccades occurred (fig. 2B,C left part). Very few express saccades occurred in the overlap situation in which the subjects payed peripheral attention until the target appeared (fig. 2B,C right part), even if the subjects were constantly cued to the saccade target position.

These results indicate that express saccades are produced if visual attention directed to some part of the visual field is interrupted before the appearance of the target. This still leaves open the question, why in total darkness, where there is neither a target for fixation nor a target for attention, no express saccades are made. To work out this point more clearly we used the ordinary gap condition and systematically increased the gap duration. The saccade target was always located 4 deg to the right of the central fixation point in order to increase the number of express saccades (Fischer and Ramsperger, 1986). In fig. 3 the

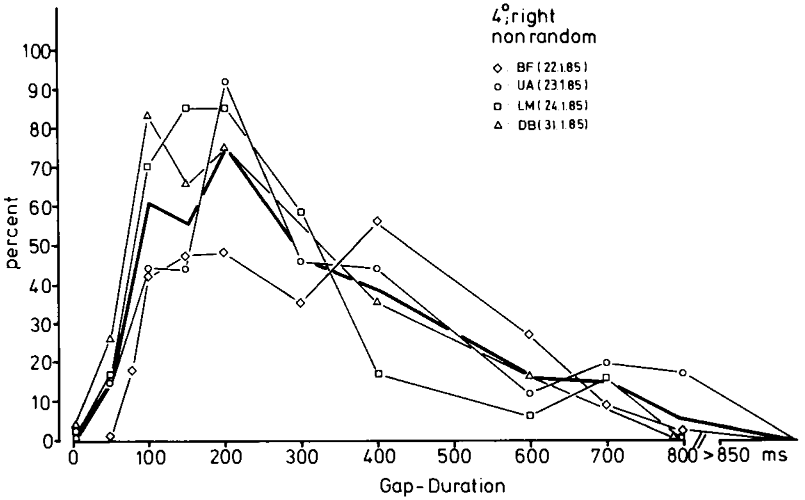

Fig. 3: Amount of express saccades (ordinate) versus gap duration (abscissa). The heavy line represents the mean of the 4 individual sets of data.

percentage of the express saccades is plotted versus the gap duration used. The order of the tests was pseudo random with respect to the gap duration. The figure shows a drastic increase of the number of express saccades between gap = 0 ms and gap = 200 ms, and a slow decrease for longer gap durations. For gap durations longer than 800 ms (corresponding to total darkness) and in the gap = 0 situation (target appearing simultaneously with the fixation point disappearance), none of the subjects produced express saccades.

DISCUSSION

In man, several populations of visually guided saccades can be distinguished in the distribution of their reaction times in different experimental conditions: an express peak between 100-140 ms and a peak of fast regular saccades between 150-200 ms in the gap condition; a broad peak of slow regular saccades around 250 ms in the overlap condition.

It is assumed that the different populations of saccades are to be attributed to different internal states of the visuo to oculomotor system at target appearance. For this, cerebral processes which elapse before the appearance of the saccadic target, are important and can partly be influenced by the external (experimental) conditions.

In the beginning it was assumed that the presence or absence of a fixation point at the moment at which the target appears, accounts for the different saccadic reaction times and especially for the occurrence of express saccades in the gap condition. However, the results presented here show that the absence of a central fixation point is not a sufficient condition to produce saccades with short reaction times: if the saccade target appeared in total darkness, or if the subjects directed their direction of gaze to a certain place in the visual field without any physical fixation point, the distributions of saccadic reaction times were hardly different from the distribution in the overlap condition showing mainly saccadic reaction times longer than 200 ms and only very few express saccades. However, if visual attention was directed to a peripheral light spot which disappeared 200 ms before saccade target appearance, the distribution of the saccadic reaction times was similar to the distribution in the gap condition, i.e. many express saccades were produced. This observation indicates that saccades with short reaction times and especially express saccades, occur, if visual attention directed to one part of the visual field is interrupted a short time before the saccade target appears. In other words: engaged visual attention at the moment of saccade target appearance abolishes express saccades. Even if visual attention of a subject was permanently oriented to the place in the visual field where the saccade target would appear, no express saccades occurred.

Thus, the disengagement of visual attention represents a necessary and time consuming process in the preparation of a goal directed saccade. Fig. 4 illustrates how the different processes - release from attention, A; decision making, D; computation of the metrics, C; afferent and efferent delay times, V and M - are assumed to contribute to the preparation of a saccade. The disappearance of the fixation point in the gap condition initiates the process A which is followed by the process D. The corresponding time periods can elapse within the duration of the gap (i.e. before the appearance of the saccade target). Therefore extremely short latency saccades can occur because their reaction times include only the processes V, C and M. On the other hand, in the presence of a fixation point (overlap condition) or a peripheral "attention target" the saccadic reaction times will be long because they also include the processes A and D which can be initiated only after the appearance of the saccade target.

The quantity of express saccades decreases with increasing gap durations above 300 ms; without a fixation point almost no express saccades occur (fig. 3). Two alternative hypotheses are proposed to explain these observations: First, the disappearance of the

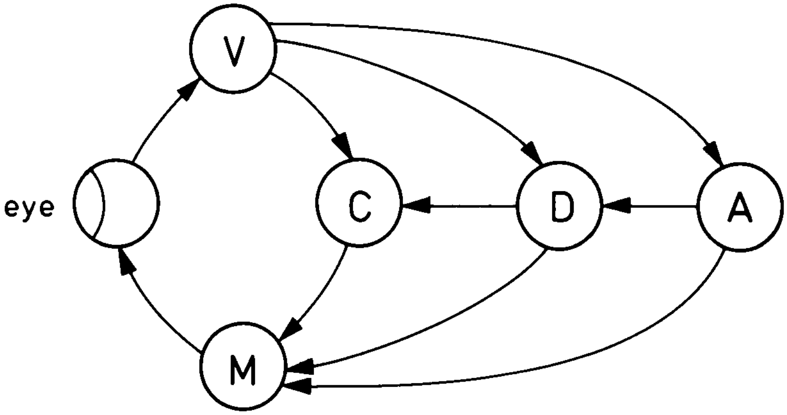

Fig. 4: Schematic diagram showing the main pathways and processes involved in the preparation of voluntary goal directed saccades. V: afferent visual structures, C: computation of saccadic metrics, M: efferent oculomotor centers, D: decision making, A: directed visual attention.

fixation point initiates the processes V and A, which activates process D. If no target appears within a time period of about 300 ms, process D will be disactivated, which would lead to a longer reaction time of the next saccade. Second, even in darkness the system could stay in the state of released attention only for short periods of time (about 300 ms after fixation point offset). If no target appears within that time period, attention is logged in and must be released again before the next saccade, which therefore has a long reaction time.

We suppose that attention directed to a visual stimulus prevents saccades during fixation. Therefore, the oculomotor system cannot produce express saccades to a second visual target in the overlap condition. This assumption is supported by the observation that "visual fixation neurons" (Mountcastle, Lynch, Georgopoulos, Sakata, and Aguna, 1975; Lynch, Mountcastle, Talbot, and Yin, 1977) in parietal cortex of the monkey (area 7) are suppressed before and during a saccade to a new target (Lynch, Mountcastle, Talbot, and Yin, 1977). These "visual fixation neurons" form a subpopulation of cells in area 7 whose discharge is modulated by visual attention (Lynch, Mountcastle, Talbot, and Yin, 1977; Robinson, Goldberg, and Stanton, 1978; Bushnell, Goldberg, and Robinson, 1981).

Therefore, we suppose that the suppression of the "fixation cells" reflects interruption of visual attention and takes a time which leads to long saccadic reaction times in the overlap condition, while in the gap condition the inhibiting visual attention is interrupted before the appearance of the new target. Furthermore, visual fixation can abolish saccades elicited by electrical stimulation of area 7A (Shibutani, Sakata, and Hyvärinen, 1984).

The specific aspect of disengaging attention as a process separate from moving and refocusing attention was also stressed by Posner, Walker, Friedrich, and Rafal (1984). Moreover, they demonstrated that this operation needs an intact parietal lobe.

The system that mediates express saccades seems to form a visuo-to-oculomotor loop which can be inhibited by (cortical) activity reflecting visual attention. The diagram of Fig. 4 suggests in addition that this loop is also under control of process D which in turn is controled by process A. This second control instance D seems to be located in the frontal lobes. The frontal eye fields are intimately related to goal directed saccades (Bruce and Goldberg, 1984) and frontal lobe lesions in man cause difficulties in suppressing reflexive glances (Guitton, Buchtel, and Douglas, 1985). It was concluded that there exists a reflex like loop (via superior colliculus) which usually is inhibited by cortical control originating from the frontal lobe.

One observation still remains unclear: the bimodal distribution of saccadic reaction times in the gap condition. Since in this condition only few slow regular saccades occur, one has to assume that in most trials process A (see Fig. 4) has elapsed during the gap between fixation point disappearance and target appearance. Only in one part of the trials, however, also process D seems to have taken place before the appearance of the target. This would lead to express saccades. In the remaining trials processes D and C have to lapse after the appearance of the target causing longer reaction times. It is still unknown what determines these different time courses.

ACKNOWLEDGEMENTS

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

COORDINATED VERGENCE FOR FRONTAL FIXATION, BUT INDEPENDENT EYE MOVEMENTS FOR LATERAL VIEWING, IN THE PIGEON

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The pigeon's retina has two specialized areas projecting respectively into the frontal binocular and into the lateral monocular fields. We analysed (EOG and video recording) the eye movements accompanying these two modes of vision. Two different oculomotor strategies occur as a function of the retinal area sollicited : an object of interest presented in the near frontal field always elicits a graded-saccadic convergence coordinated for both eyes, while a stimulus appearing in the lateral viewing field mostly triggers independent orienting saccades of the ipsilateral eye. The existence of two types of oculomotor control, for frontal and for lateral fixation, is suggested.

INTRODUCTION

The Pigeon is a diurnal bird which has a particularly well developed visual system with the following outstanding features :

- large laterally placed eyes which provide a panoramic viewing field of about 300° while keeping a considerable frontal binocular overlap of about 30° (Rochon-Duvigneaud, 1943 ; Martinoya, Rey & Bloch, 1981) (see **Fig. 1**).
- a densely packed cone-predominant retina with two regions clearly delimited by the proportion of cones containing coloured oil droplets : the "red field" in the dorso-temporal quadrant, projecting frontaly into the binocular field and the "yellow field" in the other quadrants, projecting to each large external uniocular field (King-Smith, 1969 ; Bloch & Maturana, 1971).
- two areas of higher cellular density : the fovea proper near the axis of the eye within the yellow field, projecting laterally some 80° behind and 5° below the horizontal plane of the beak (Galifret, 1968 ; Bingelli & Paule, 1969), and the "area dorsalis" near the center of the red field (op. cit.), projecting frontally some 20° below the beak in the direction of best optical binocular viewing (Martinoya et al., 1981) (see **Fig. 1**).
- a rich retinal connectivity (Yazulla, 1974) with two separate central projections, one to the large and well laminated optic tectum, and the other to a neatly defined homologue of the mammalian lateral geniculate (Karten & Revzin, 1966 ; Karten & Nauta, 1968).

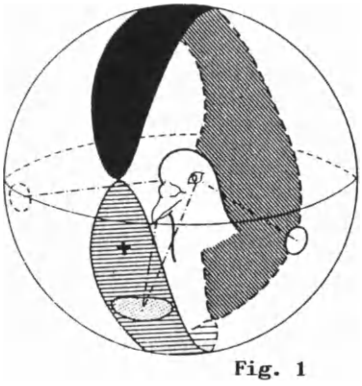


Fig. 1

A pictorial representation of the pigeon's viewing field is shown in **Fig. 1**. The lateral monocular fields (in white) correspond to the projections of the yellow fields and contain the projection of the foveae (represented by two circles). The binocular fronto-ventral field (horizontal hatching) corresponds to the projection of both red fields and contains the overlapped projection of both dorsal areas (dotted oval). The postero-dorsal blind region (black and diagonal hatching) is only approximately indicated.

Visual fields and functional specialization

The ensemble of the above described peculiarities of the pigeon's visual system suggests that frontal and lateral viewing are functionally differentiated. Since the great majority of the animal's visual capacities had been tested only in conditions of frontal viewing (e.g. Hodos, Leibowitz & Bonbright, 1976), we have done a comparative analysis of frontal and lateral visual functions in this bird, using a method of "behavioural fixation" (Bloch & Martinoya, 1983).

The collected information strongly supports the existence in the pigeon of a double mode of vision : one for frontal binocular viewing, mediated by the area dorsalis, specialized in the fine resolution and depth judgements of static near objects (Martinoya & Bloch, 1980 ; Bloch & Martinoya, 1982), and the other for lateral viewing, mediated by the fovea centralis, specialized in the detection of distant moving targets (Martinoya, Rivaud & Bloch, 1983). The pigeon's retinal structure and the placement of the eyes would allow both modes of vision to occur simultaneously.

Visual exploration and eye movements

We know that pigeons, as most lateral-eyed birds, visually explore their environment with fast head movements which have been well studied (Dunlap and Mowrer, 1930 ; Fite, 1968 ; Friedman, 1973). According to Walls (1962), if a zone of higher cellular density exists in a retinal region, there must coexist some mechanism of fixation that will allow the retina to glide until the image of the object of interest falls upon this particular zone.

Little attention has been given to eye-in-head displacements in the pigeon as if the extreme head motility sufficed for visual exploration without the necessary participation of the oculomotor system. In free-moving pigeons head movements alone could account for lateral fixation with the fovea, but for frontal fixation, converging ocular movements must occur in order to place the images of the object on corresponding points of the dorsal areas.

METHOD

In order to test this hypothesis we analyzed the oculomotor behaviour by recording spontaneous and elicited horizontal eye movements (EM) from head-restrained pigeons and from free-moving animals during pecking. Electrodes were implanted under Ketalar anaesthesia (40 mg/Kg) in the orbital arch near the anterior and posterior canthi of each eye ; a reference electrode was placed on the cranial bone. The 5 electrodes were joined to a connector fixed to the skull. A metallic piece was likewise fixed to the skull in order to immobilize the animal's head when needed. The electrooculogram (EOG) was amplified and recorded (DC to 30 or 100 Hz) on an ink dynograph recorder (Beckman, Type R 411).

EXPERIMENTS

Eye movements in head-restrained pigeons

One of the main problems for studying EM in these conditions is to attract the animal's attention to a target. We initially tried to employ procedures which have proved successful with mammals (e.g. Fuchs, 1967). The first was to present a controlled visual stimulus, the displacement of a small light emitting diode within the frontal binocular field at 20 cm from the animal's eyes. No signs of visual following could be elicited, the pigeon seemingly paying no attention to the light. We then tried to develop an operant conditioning paradigm by reinforcing any spontaneous EM to the stimulus onset with a drop of water directly applied to the beak of a water-deprived bird. No conditioned ocular responses could be obtained. Finally we found that the efficient, though unquantifiable procedure was the sudden presentation of novel and large moving objects within the pigeon's panoramic visual field. In contrast to Nye (1968) who was unable to measure shifts larger than 5°, we have recorded with this highly unorthodox procedure, EM as large as 17° from "resting position" (Bloch, Rivaud & Martinoya, 1981, 1984).

Fig. 2 (taken from op. cit.) shows the direct EOG obtained when a piece of crumpled paper hanging from a rod was wiggled around the animal in the directions schematized in the lower left drawing. The EOG polarity was chosen so that forward movements of both eyes (convergence) are represented by converging traces. As can be seen, as soon as the stimulation enters the animal's left monocular field (**Fig.** 2, B-L) the left eye makes a swift backwards saccade which is not coincident with any saccade of the right eye ; then the left eye does a kind of staircase pursuit, following the stimulus until it enters the binocular field (F), both eyes at that moment showing coordinated converging saccades; this same sequence was observed for the three successive circlings around the animal.

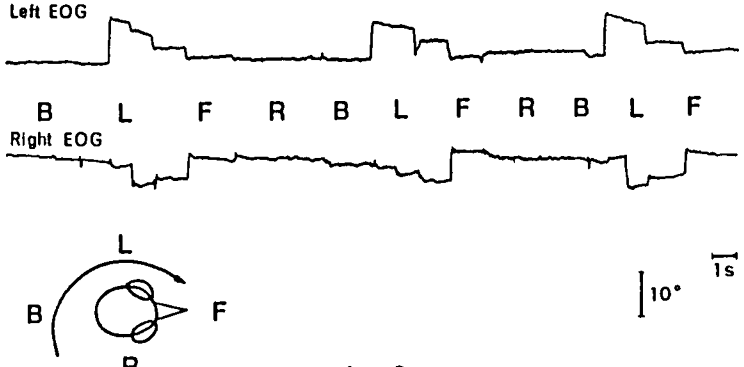
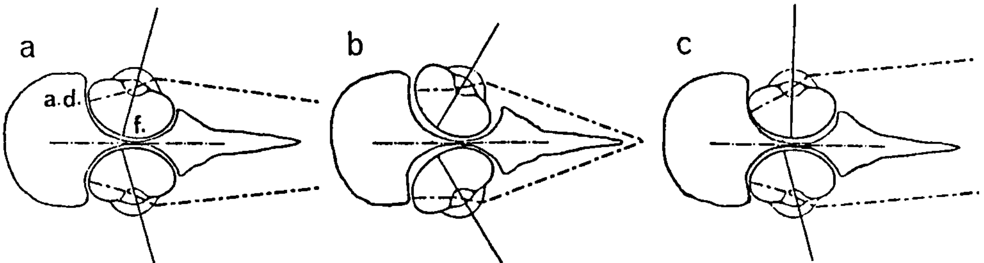


Fig. 2

It is interesting to remark that when the stimulus leaves the left eye field in the rostro-caudal direction (F-R), there is no response. The same direction-dependent efficacy of stimulation is observed in the pigeon for the optokinetic nystagmus (Huizinga & Meulen, 1951 ; Gioanni, Rey, Villalobos and Bouyer, 1981 ; our own observations). We have also observed slow drifts and rapid oscillations similar to the ones described by Nye (1968), and, occasionally, conjugate movements.



Both eyes are at "resting" position (unknown fixation)

Both eyes have rotated (17°) forward (frontal fixation)

Only left eye has rotated (13.5°) backward (lateral fixation)

Fig. 3

We have schematized in **Fig.** 3 the positions of eye-in-head and the direction of the lines of sight expected with the eyes "at rest" (a), during frontal fixation to a near target (b) and during lateral fixation (c). In this last situation with the left eye "looking backwards", we do not know whether the animal is simultaneously fixating something else with the right eye.

We define the lines of sight for frontal and lateral fixation as the external projection of each "area dorsalis" (a.d.) and each fovea (f.), respectively.

The peculiarities of the pigeon's visual system and the kinds of EM just described, suggest the existence of at least two different mechanisms of oculomotor control : one being functional during near frontal fixation, commanding coordinated converging saccades, and the other being functional during lateral fixations, commanding independent uniocular saccades.

Eye movements in free-moving pigeons

The question remained open as to whether the type of EMs observed in the head-restrained conditions are or not functional in a free-moving situation. In order to investigate this, we chose to analyse oculomotor behaviour during pecking at grains, a highly stereotyped frontal action whose spatio-temporal parameters have been well studied (Zeigler, 1980 ; Zweers, 1982 ; Goodale, 1983). We recorded the EOG from pigeons who had been trained to eat grains in a narrow cage with one transparent wall, under stroboscopic illumination. The wire coming from the connector was attached in a loose loop onto the ceiling and the animals reached for the grain without seeming disturbed.

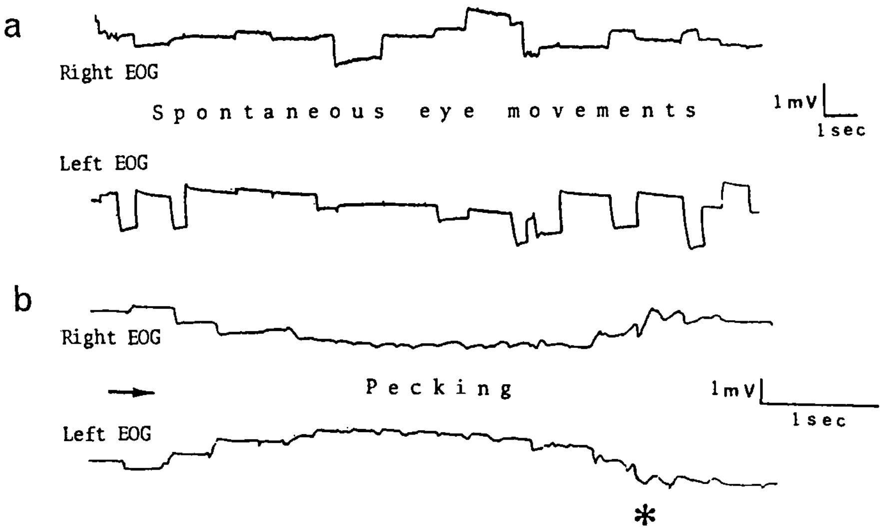


Fig. 4

Figure 4 depicts EM in one typical animal. In a), spontaneous saccades (some coinciding and others independent for the two eyes) are observed while the animal is just looking around. In b), the typical coordinated converging saccades (already observed with head-restrained pigeons subjected to a frontal stimulation) is seen during pecking, i.e. while the animal is "looking" at the grain with frontal fixation. It is clear from the figure that the maximal convergence is reached by successive saccades synchronized for both eyes. Eyes remain converged during pecking ; once the grain has been grasped and the animal lifts its head with the grain in its beak, the convergence is reduced by steps until the grain is swallowed (*).

Thus, the basic oculomotor behaviour in the pigeon is the same in free-moving and in head-restrained conditions, a specific vergence mechanism always being functional during frontal fixation.

In order to directly correlate the positions of head-in-space and eyes-in-head during pecking, a video camera (Sony Betamax) recorded simultaneously the profile of the animal, the EOG traces displayed beside the cage on two LED analog panel meters, and the count of video frames. This set-up allowed us to measure changes in the eye and head positions every 20 ms. We could thus confirm that as the animals lowered their heads during feeding, they typically approached the grain by alternating head thrusts and stops (Zeigler et al. 1980 ; Goodale, 1983). We measured the eye-to-grain distance and the EOG traces on those video frames corresponding to the 100-200 ms head stops. A schematic illustration of the successive head positions (1 through 4) and of the respective EOG traces as taken directly from the video images is shown in **Figure** 5 (taken from Martinoya, Le Houezec & Bloch, 1984). Head stop 1 corresponds to the end of the exploration stage, the eyes in this case seemingly in the "resting" position. Head stop 3 is the last one before the ballistic descent with the beak open to seize the grain (head position 4). The corresponding EOGs (bars on the right, upper for right eye, lower for left eye) are displayed in such a way that converging traces correspond to convergence of the eyes.

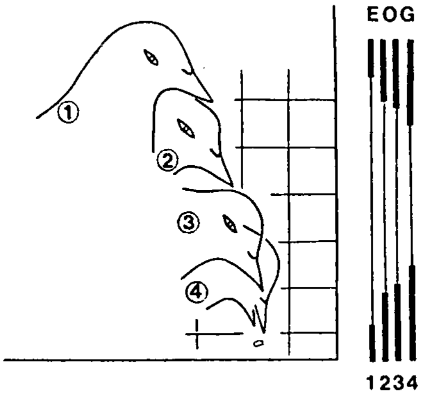


Fig. 5

For eye rotations smaller than 15°, changes in EOG (uV) are directly proportional to the magnitude of the rotation in degrees ; thus the sum of the EOGs and the eye convergence are linearly related. If eye convergence is equated to grain parallax ($P = 2 \tan^{-1} (b/2D)$, where D = eye-to-grain distance and b = interocular distance), a linear relation must also exist between the sum of both EOGs and grain parallax.

Figure 6 (adapted from op. cit.) represents eye convergence as a function of eye-to-grain parallax. Each experimental point corresponds to the measures obtained for individual head stops in the course of 9-13 grain descents. The left graph corresponds to a free viewing pigeon and the right graph to a bird pecking with one frontal field occluded. We found the expected linear correlation between

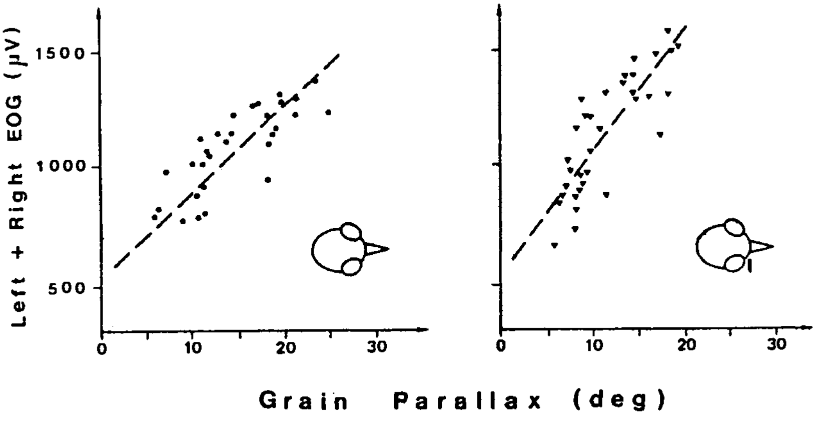


Fig. 6

the sum of the EOGs and binocular grain parallax. The slope of the best fit regression line for the experimental points is 37.7 uV/degree. This value is close to the one obtained comparing direct measurements of eye rotations with the concomitant EOG changes (29 uV/degree ; Martinoya et al., 1981).

The graded convergence may be taken as further evidence for a frontal mode of fixation and could serve the animal to keep the target accurately projected on the dorsal areas. Such coordinated vergence movements could be the result of each eye pointing independently to the same target and not therefore of a bilaterally commanded coordination. The fact that coordinated vergence is maintained when one frontal field is occluded (see **Fig. 6**, right graph), clearly implies the existence of a bilateral control mechanism of vergence.

Eye movements after section of interhemispheric commissures

In man the integrity of the interhemispheric connections seems to be necessary for vergence EM to occur (Westheimer & Mitchell, 1969). Birds do not possess the equivalent of the mammalian corpus callosum ; instead, the existing interhemispheric connections are grouped in several commissures (anterior, posterior, tectal and supraoptic). In the case of the pigeon, though all optic fibers cross at the chiasm, there are bilateral thalomofugal projections which cross at the level of the supraoptic decussation (Miceli & Repérant, 1982).

In a recent series of experiments in our laboratory (in collaboration with Sally McFadden, unpublished observations) we have analysed EM in pigeons before and after section of different commissures. In **Figure 7** we show an example of the oculomotor behaviour in a free-moving pigeon 8 days after section of the supraoptic decussation.

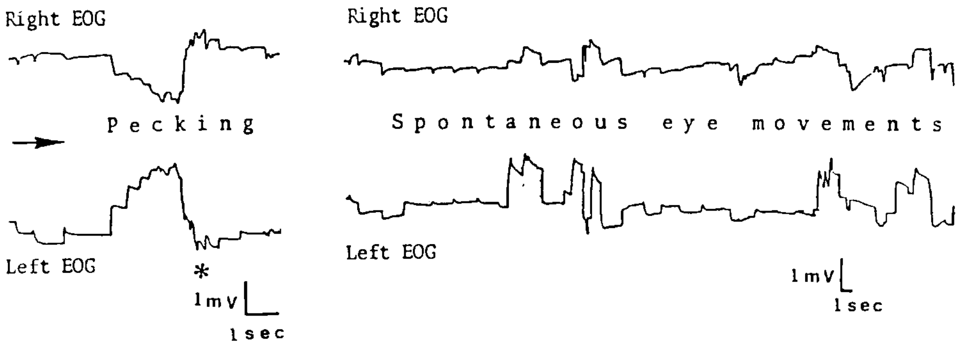


Fig. 7

As can be seen, both spontaneous saccades (coinciding or independent for each eye) as well as the typical vergence movements during pecking are preserved after the section. Though basic oculomotor behaviour is not affected by the lesion, we did however observe some instability in the converging movements and an imprecision in pecking. Errors in pecking and performance deficits in depth discrimination tasks have been reported after sections of the supraoptic decussation and tectal commissure (McFadden, 1984).

GENERAL DISCUSSION AND CONCLUSIONS

It is certainly interesting to find a vertebrate (the pigeon) who not only can move the eyes either in unison or independently, but whose oculomotor strategy (unilateral or bilateral command) will depend on the retinal area which is being sollicited : an attention-calling stimulus presented in the lateral field of one eye from any direction of space, elicits an ipsilateral orienting saccade towards the target which only sometimes is coincident with movements of the contralateral eye ; contrarily, an attention-calling stimulus presented in the frontal binocular field of viewing always elicits coordinated converging saccades. It is possible that such a bimodal oculomotor behaviour is present in other lateral-eyed vertebrates which have binocular overlap, but we found no pertinent references in the literature.

It seems on the other hand a quite remarkable feature for a lateral-eyed bird to possess an oculomotor mechanism which enables the animal to maintain a frontal target continuously projected on the binocular field ("area dorsalis"). The fast graded converging saccades observed in the pigeon, however, contrast with the slow and smooth converging movements observed in man when a target is approached in the frontal field (Rashbass & Westheimer, 1961). There is probably a quite different organization of bilateral command for eye movements leading to convergence in primates and pigeons ; nevertheless the very existence of this mechanism raises the question as to whether the pigeon uses binocular cues for depth judgements during frontal binocular fixation similar to the ones used by a frontal-eyed animal. A recent study in our laboratory suggests that eye convergence in fact is used for programming the final ballistic descent of the pigeon onto the grain (Martinoya, Palacios & Bloch, 1984).

Investigations of EM in relation to attention-calling stimuli in other lateral-eyed vertebrates are very scarce. In the case of the rabbit, coordinated vergence movements have been reported during visuo-motor tasks (Zuidam & Collewijn, 1979). Convergence movements ranged from 2.5° to 8.5° during active approach as well as during head restrained tests. Collewijn (1977) has compared the general pattern of EMs in the free rabbit to that of primates, the main difference being the lack of microsaccades and of smooth pursuit, probably due to the absence of a true foveal organization.

In the case of the pigeon, one could aproximate the frontal mode of vision (binocular overlap, specialized retinal areas, coordinated vergence) with frontal foveal vision of primates, and the lateral mode to that of the chameleon, an extreme case of uncoordinated ocular motility (Mates, 1978). The analysis of visual processes in the pigeon allows to compare in the very same animal, visual specializations and oculomotor functions which appear separately in other species and may contribute to the comparative study of visual systems in frontal and in lateral-eyed vertebrates.

The reported data on the pigeon and what is known from the rabbit invite to revise our conceptions on directions of viewing. We are too much in the habit of considering visual strategies (and in planning visual experiments) in reference to foveal vision : in fact the term "line of sight" has become equivalent to "external projection of the central fovea". The acceptance of more than one line of sight, in terms of a visual trident as suggested by Rochon-Duvigneaud (1943) may be necessary for a better understanding of vision in the lateral-eyed vertebrate.

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EYE MOVEMENTS: From Physiology to Cognition
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KINAESTHETIC AND MOTOR EFFECTS OF EXTRAOCULAR MUSCLE VIBRATION IN MAN

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Painless well patterned vibrations, with an increasing frequency from 10 to 80 Hz, applied to either medial or lateral rectus of a subject's eye (right, left or both) were found to induce directional perceptual and motor effects which were closely related to the postural context. The same was true for superior and inferior recti. Illusory and/or actual movements of head, trunk or whole body were produced depending on postural constraints (head free or fixed, standing or seated subject) . Likewise, illusory directional shift of a visually fixed target in darkness during extraocular muscle vibration, was reported by subjects. The contribution of extraocular proprioception to the coding of eye, head and body position in relation to postural and environmental conditions is discussed.

INTRODUCTION

In addition to the retinal coding of object positions in extrapersonal space, it has been suggested that the direction of gaze, i.e. the position of the eye in space, may play a decisive role in human spatially oriented behavior as a whole (Howard (1982)). The exact nature and origin of such an extraretinal signal have not yet been firmly established however. In particular, the question as to whether a proprioceptive contribution arises from extraocular muscles is rather controversial. There is still discussion nowadays as to the respective roles played by inflow and outflow information in the neural coding of eye position itself, and in that of eye position in relation to head, trunk, and whole body posture (Mc Closkey (1981), Stark and Bridgeman (1984), Steinbach and Skarf (1985)).

This problem has been approached experimentally by manipulating either the extraocular muscle afferents or the efferents. In the first case, the method consisted of passively stretching the subject's extraocular muscles in order to manipulate their proprioceptors. Unfortunately, although their experimental conditions were almost the same, two authors came to opposite conclusions. Brindley and Merton (1960) reported that no eye position sense could be observed when the eyes were closed, and that no visual illusion or mislocation of the direction occurred when the non stretched eye was then opened. Skavenski (1972), on the contrary, has stressed the fact that afferent cues from muscle spindles or tendon organs play an important role in a subject's awareness of his eye position.

In the second case, on the basis of the paralysis of extraocular muscles suppressing the proprioceptive afferent channel, some authors have drawn attention to the role of the efferent copy. Illusory displacement of the visual scene was reported by subjects when they attempted to move their paralysed eye (Helmoltz (1867); Siebeck, (1954); Brindley, Goodwin, Kulikowski and Leighton

(1976); Matin, Picoult, Stevens, Edwards and Mac Arthur (1982)). Likewise, large overshoots in a pointing test were observed in patients with one rectus paralysed when the visual target appeared in the same hemifield as the paralysed muscle (Perenin, Jeannerod and Prablanc (1977)). The role of outflow was also shown by the demonstration that eye press causes the visual scene to be perceived in motion (Stark and Bridgeman (1984)).

It should be noted, however, that all these results show variations dependent on the experimental conditions; namely the muscle pulling technique or eye press, the degree of eye muscle paralysis or the environmental cues such as light, background (Matin et al. (1982)), and training of subjects (Skavenski (1972)).

This being so, it seems likely that part of a subject's awareness of his eye position may originate from the muscle spindles of extraocular muscles. Indeed, it is a well known fact that, in man, the eye muscles are richly endowed with proprioceptors of the muscle spindle type (Cooper and Daniel (1949); Cooper, Daniel and Whitteridge (1955); Matthews (1972)). They are very dense and their functional properties are very similar to those of the skeletal muscle spindles (Cooper, Daniel and Whitteridge (1951); Whitteridge (1960); Bach y Rita and Ito (1966); Richmond, Johnston, Baker and Steinbach (1984)). On the other hand, various studies on man and animals have shown that the muscle spindles are very sensitive to low amplitude mechanical vibrations (Bianconi and Van der Meulen (1963); Matthews (1972); Burke, Hagbarth, Lofstedt and Wallin (1976)). The application of vibration trains to the tendon of a limb muscle in man is able to activate the muscle spindle afferent channel which responds one to one to stimuli between 1 and 100 Hz (Roll and Vedel (1982), Vedel and Roll (1983)). Moreover, this kind of vibratory stimulation can induce kinaesthetic illusions and associated motor responses, the directions of which correspond to the actual stretching of the vibrated muscle. These effects are frequency dependent and the illusory or actual movements always correspond to low velocity displacements (Goodwin, Mac Closkey and Matthews (1972); Roll, Gilhodes and Tardy-Gervet (1980)).It is thus possible in man, in the absence of any actual movement, to artificially induce proprioceptive messages which are almost exact copies of the natural proprioceptive feedback (Roll and Vedel (1982)).

Since we possess this means of activating muscle stretch receptors by vibrations, and in view of the density of muscle spindles in extraocular muscles, we attempted to specifically activate the eye muscle proprioceptors in man.

Vibrations applied to extraocular human muscles were found to be capable of eliciting directional kinaesthetic illusions and involuntary motor responses which depended strictly on the postural context and the position of the vibrator around the eyeball. Illusory and actual movements of the head, trunk or whole body were produced depending on the postural constraints: head free or fixed, seated or standing subjects. Likewise, illusory directional shifts of a visually fixed target in darkness were also reported by subjects when extraocular muscle vibrations were applied.

METHOD

Mechanical vibrations with an amplitude of 0.1 to 0.2 mm peak to peak (rectangular pulses: 3ms) were applied to various points on the periphery of the eyeball, by means of a mini electromagnetic vibrator (L.D.S. type 101) on which small probes could be adapted to the subject's eye morphology. Their length and shape varied according to whether medial or external muscles were to be vibrated. The contacting surface was polished and had a concave shape which could be easily adapted to the eyeball.

The vibration train duration was 5 seconds; the frequency could vary from 1 to 100 Hz but the usual frequency was 70 Hz or increasing frequency from 0 to 70 Hz.

Under the standing condition, postural sways were recorded from four strain gages which were enclosed in the stabilometer set under each subject's foot.
Under the seated condition and with the head free, the subject's trunk was fastened to a fixed seat back. Horizontal head movements were recorded by a high precision potentiometer mounted on a head helmet.

Under the opposite condition -trunk free and head restrained- the subject was seated in a rotating chair on the axis of which was also fixed a potentiometer for recording the horizontal body rotations. A head and chin-rest device was added to prevent any head movements.
Lastly, under the target viewing condition, the subject was seated in the dark, monocularly facing a small electroluminescent diode located 57 cm from him, at eye level.

The subject's eyes were closed under all conditions except for the last. Either one eye or both eyes alternately were vibrated. When both eyes were stimulated, vibrations were applied to the same muscle of each eye (two inferior and two superior recti), or to the synergist muscles, i.e. the lateral rectus of one eye together with the medial rectus of the other eye (Fig.1).

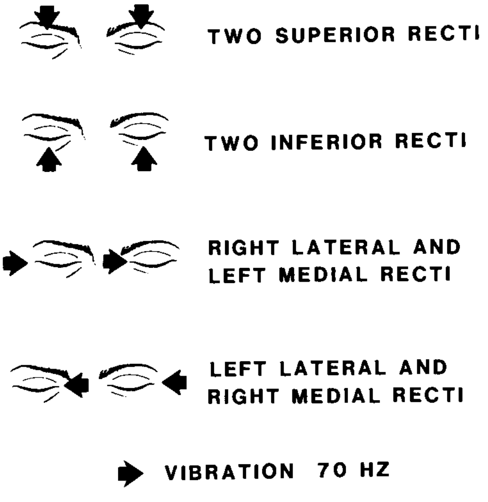

Figure 1

Experimental conditions of stimulation of both eyes. The arrows correspond to the simultaneous application of vibrations to both eyes, leading probably to the selective activation of proprioceptors of different extraocular muscles. The single eye vibration is not represented.

Before testing, the apparent lengthening of a visual target in an expected direction perceived by the subject in response to application of low frequency vibration to a given muscle, was used to check that the vibrator was correctly placed on the eye muscle.

Experimental results and quantitative analysis deal particularly with the perceptual and motor effects of eye muscle vibration in subjects with an upright standing posture. A preliminary report is given in connection with the other conditions.

RESULTS

Postural effects of extraocular muscle vibrations

Application of low amplitude mechanical vibration to the extraocular muscles of a standing subject with his eyes closed elicited whole body shifts, the direction of which was found to depend strictly on which muscle was vibrated. The latency of these effects varied in the range of 1 to 2 seconds; this is illustrated by posturograms which correspond to the combined time recordings of lateral (X) and anteroposterior (Y) components of postural forces. Figure 2 summarizes the postural vibration-induced effects of the simultaneous vibration of both eyes under all four different experimental conditions of stimulation.

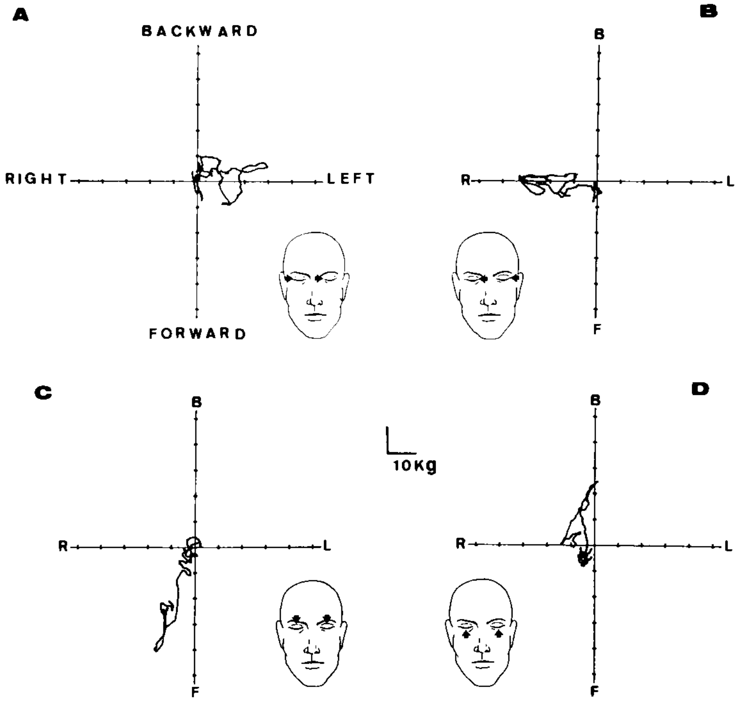

Figure 2
Directional postural effects of the application of high frequency vibrations (70 Hz) to homonymous extraocular muscles of both eyes. The arrows indicate the stimulated muscles. The corresponding stabilometric recordings show the postural force variations during the stimulation (5 sec.). Note the specific directionality of postural sways corresponding to each stimulated muscle.

Simultaneous vibrations of the two superior recti resulted in a whole body displacement forward (C) whereas a backward shift was observed during vibration of the two inferior recti (D).When the stimulation was applied simultaneously to the lateral rectus of the right eye and the medial rectus of the left eye (A), a leftward displacement was elicited and vice-versa (B).

These postural effects of extraocular muscle vibration may also be analysed through independent recordings of the force variations on X and Y axis during pre, per and post vibratory periods.

The postural effects of the simultaneous vibration of the two superior recti in a standing subject for a duration of 5 seconds and at a frequency of 70 Hz, are described in Figure 3. The application of vibrations first resulted in a considerable increase in the equilibrium oscillation amplitude in the forward direction when compared to the control period, and was immediately followed by post vibratory oscillations in the opposite direction. The lower part of the diagram shows the position error histograms computed from time recordings on both axis. They illustrate the extent of postural equilibrium alterations in terms of mean position variations as well as their dispersion. Very few variations were observable on the X axis histograms in pre, per and post vibratory sequences, whereas an increasing spread of Y axis histograms due to the subject's disequilibrium could be observed during vibrations and, to a lesser extent, in the post stimulation sequence.

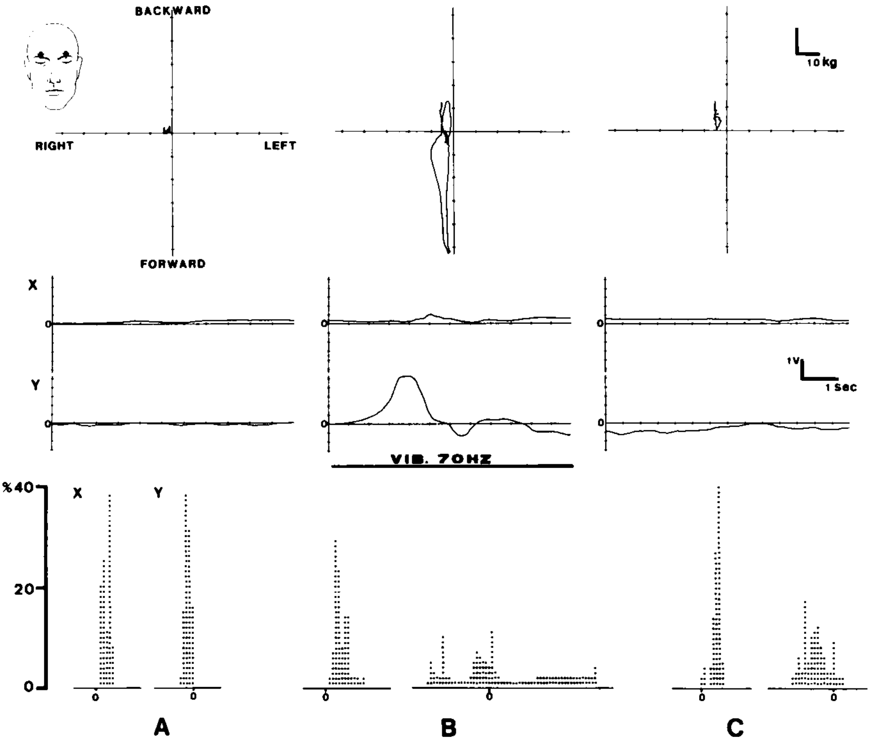

Figure 3

Postural effects of vibratory stimulation of both superior recti in pre(A), per(B) and post(C) vibratory periods.
From top to bottom: stabilometric recordings; time recordings of postural force variations on X lateral axis and Y anteroposterior axis; position error histograms on X and Y axis. The median horizontal line represents the onset and duration of the stimulation (vibration: 70Hz, 5sec.).

Individual trials (A), and mean results (B) for all subjects under all four conditions involving combined vibrations of both eyes are described in Figure 4. The vectors correspond to the polar coordinates of the maximum amplitude of displacement recorded during one trial. The modulus length of the vectors indicates the magnitude of the effects, and its angular position the direction of the postural shift. Vibration of the inferior rectus leads to backward body displacements, and vibration of the superior rectus to forward displacements. Likewise, vibration of one external and one medial muscle leads to lateral displacements. No significant difference was observed between the effects of single muscle stimulation and that of a pair of homonymous muscles.

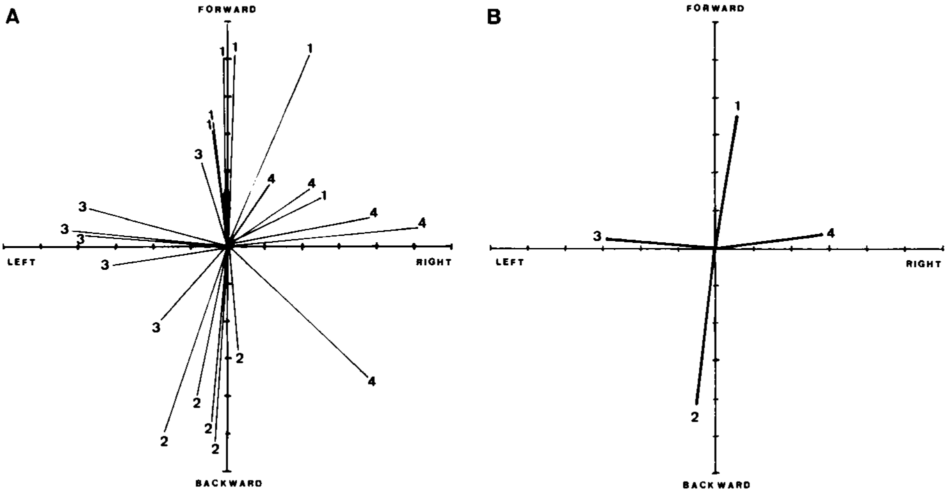

Figure 4

Groups of individual(A) and mean(B) vectors corresponding to various combinations of extraocular muscle stimulation.1) two superior recti; 2) two inferior recti; 3) lateral rectus of right eye together with medial rectus of left eye; 4) lateral rectus of left eye together with medial rectus of right eye.
For each vector the modulus length signals the individual or mean maximum amplitude of the postural sways; its angular position indicates the direction of the shift.

As shown in Figure 5, the mean amplitude of postural shift induced by vibration depends on the frequency of vibratory stimulation. The posturograms show one subject's increasing forward displacement when a 5 second vibration, increasing in steps from 20 to 100 Hz, was applied to both inferior recti. This relationship between vibration frequency and the mean amplitude of the postural sway is illustrated in the lower part of the diagram. Both the path length and the maximum amplitude varied as a function of the vibration frequency.

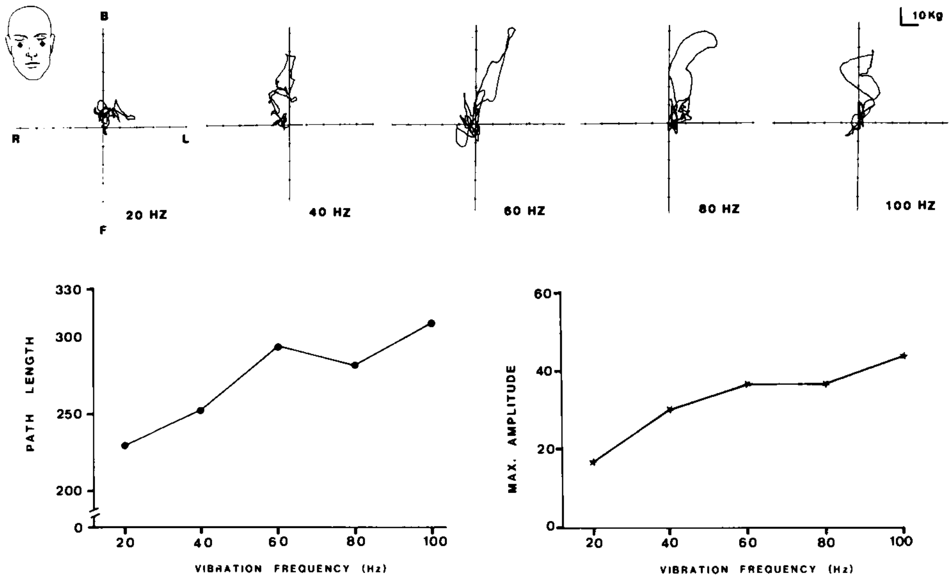

Figure 5

Effect of the vibration frequency on the amplitude of the postural sways.

Upper part: individual posturograms show the increasing amplitude of the backward shift induced by the inferior recti vibration of the both eyes with an increasing frequency from 20 to 100 Hz.

Lower part: vibration frequency with respect to the path length (left graph) and the maximum amplitude (right graph) of the postural sway.

Kinaesthetic effects of extraocular muscle vibrations

Besides these postural effects of extraocular muscle vibration, other perceptual effects such as kinaesthetic illusions can be elicited. These illusions of movement can affect the head, the trunk or the whole body depending on the postural context (Fig.6 A.B.C.).

Preliminary observations show that the direction of these kinaesthetic illusions depends on which extraocular muscle is vibrated. The perceived sensations are those of a slow movement, that is a movement of some degrees per second. Their latency varies from 1 to 2 seconds and they stop when the stimulation stops. Their subjective content is that of a slow, continuous movement which is very similar to the vibration-induced kinaesthetic illusions previously described in connection with skeletal muscles (Roll et al. (1980)).

When the subject was seated with his head free (A), the application of a vibration train to the lateral rectus of one eye, or to homonymous muscles of both eyes elicited an illusory sensation of head rotation, the direction of which corresponded to a rightward horizontal rotation in the case of left lateral vibration, and a leftward horizontal rotation in that of right lateral vibration.

Likewise, vertical head-down sensation was experienced by subjects who underwent superior muscle vibrations and a head-up sensation by those who underwent inferior muscle vibrations. After a few seconds, the same vibratory stimulation generally elicited involuntary slow movements of the head in the same direction as that of the kinaesthetic sensation.When the subject's head was fixed by means of a mechanical device (B), vibration of the same lateral muscles induced kinaesthetic trunk illusions in the direction previously described for the head. Stimulation can also induce an involuntary trunk rotation in the same direction as that of the head in this situation.

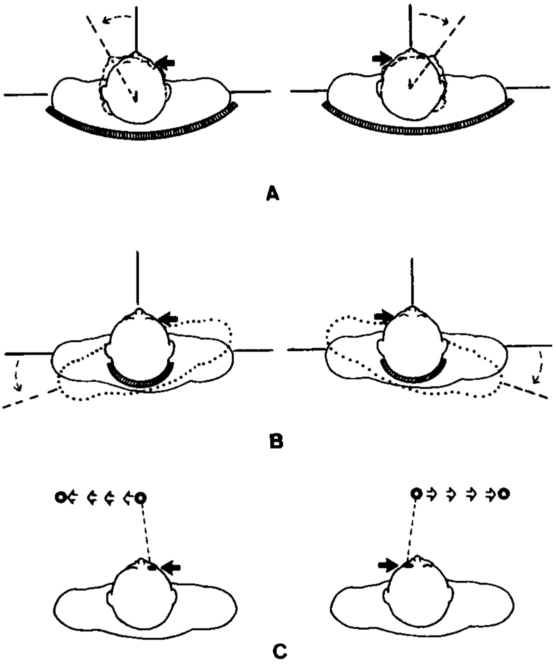

Figure 6
Kinaesthetic and visual illusions induced by vibration of the right lateral rectus (on the left) and left lateral rectus (on the right).
A) head free: illusory sensation of head rotation.
B) head fixed: illusory sensation of trunk rotation.
C) Monocular fixation of a luminous target: extraocular muscle vibration induced an illusory displacement of the target.

Figure 6C shows the last experimental condition we studied. Vibrations were applied to extraocular muscles when the subject was looking monocularly at a small visual target in darkness. The vibratory stimulation resulted in a slow displacement of the visual target, the direction of which depended on the vibrated muscle.As for the postural and kinaesthetic effects, vibration of the inferior rectus induced an upward target shift and conversely a downward shift occured under superior rectus vibration.External rectus vibration elicited an illusory target displacement in the medial direction and vibration of the medial rectus a displacement in the external direction.

No clear eye movement sensation was reported by subjects in any of the situations studied. Moreover, preliminary recordings of eye movements by E.O.G showed that no eyeball displacements took place during the vibratory sequences.

DISCUSSION

Our assumption that extraocular proprioception exists in man and that it contributes to the regulation of the spatially oriented behavior is based upon the following experimental data.

Extraocular muscle vibration entails perceptual and motor effects, in which each muscle has its own directional specificity .
This same directional specificity was found to exist in kinaesthetic, postural and visual extraocular muscle vibration-induced effects.
Under all our experimental conditions, the direction of both illusory and actual displacements was always that which corresponded to the stretch of the vibrated extraocular muscle.
At the postural level at least, the magnitude of the effects increased as a function of the stimulation frequency up to 80-100 Hz.

Besides showing the decisive role played by the extraocular muscles in the coding of eye, head and body position with respect to postural and environmental conditions, these data are perfectly consistent with those extensively described in the case of skeletal muscle vibrations (Goodwin et al. (1972); Roll et al. (1980); Roll and Vedel (1982)). Behavioral and neurophysiological results converge, showing the existence in man of a conscious coding of limb or whole body movements from proprioceptive cues originating mainly in stretched muscle. Kinaesthetic illusions and associated motor activities can easily be elicited by vibratory stimulation of limb muscle tendon. In addition, microneurographic recordings of muscle spindle activity in man have shown these receptors to be very sensitive to mechanical vibrations, and their response frequency to be proportional to the vibration frequency in the 1 to 100 Hz range in the case of primary endings (Burke et al. (1976); Roll and Vedel (1982)). In extraocular muscles, vibration induces low amplitude directional displacements of the eyeball leading probably to selective high frequency stretching of the muscle precisely stimulated. This latter point is worth mentioning because, if the vibrator probe undergoes even a small displacement on the socket bone or on the lids, the reported perceptual and motor effects are no longer obtained.

As with the skeletal muscles, painless vibration trains applied to the eye muscles might thus be thought to induce almost selective proprioceptive messages. However, under closed eye conditions, these messages do not seem to be decoded in terms of actual conscious eye movement, but more like conscious sensations of movement of the head, trunk and whole body depending on the postural context in which they occur. Under this condition, the absence of eye movement perception may result from a sensory masking effect since the cornea and lid tactile receptors are also very sensitive to low amplitude high frequency vibration, and give rise to powerful cutaneous vibratory sensations(Vedel and Roll (1983)).On the contrary, when the subject looks at the target, the proprioceptive input arising from extraocular muscles actually seems to be decoded as an eye movement since the target is perceived by the subject as moving in the expected direction in relation to the stimulation site. In this case, when the eyes are open and the target motionless, the proprioceptive signal elicited by vibratory stimulation of extraocular muscles informs the Central Nervous System that the eye is moving whereas the retinal image remains stable. This occurs for example during a smooth pursuit situation. Here the movement cue is interpreted as a target displacement. A similar effect has been reported in Lackner and Levine's experiment (1978), where the subject in darkness saw the luminous target attached to his index top moving while his arm was being vibrated by the experimenter. This illusory arm movement induced by muscle tendon vibration has also been interpreted as a target displacement in the same direction as the illusion. Likewise, Matin et al.(1982) have reported the illusory displacement of a visual target which was fixed in darkness by a subject whose eye was partially paralysed with curare. In addition, the direction of this illusion depended on the head position, and it disappeared on the illumination of the surroundings.

Although they do not reveal the exact neurophysiological process involved, these data suggest that the central processing of extra retinal signals depends to a great extent on the visual and/or postural context in which the experiments were carried out. The results described here could be interpreted along these lines. In the absence of retinal information, when the subject's eyes are closed,the extraretinal signal of eye muscle origin may not be assigned to the coding of the position of the eye itself, which would serve no useful purpose, but rather to the coding of the various body segment positions usually associated with eye rotation. With regard to the nature of the postural constraints involved, the head, the trunk, or the whole body might be concerned with such processing. The existence of a large amount of functional coupling between these various mobile segments is thus confirmed from perceptual and motor points of view by our experimental manipulation of eye proprioceptive feedback. It is possible that this kind of "proprioceptive coupling" might result from behavioral patterns which usually link eye movements to those of other mobile segments. This might occur, for instance, during the early eye-head directional linkage when a target is appearing on the periphery of the visual field; in particular, in the well-described "predictive mode" of eye-head coordination (Bizzi (1974)) when the conditioned monkey is able to turn its head in anticipation of the appearance of the target. In this case, contrary to the ordinary sequence (triggered mode), head turning precedes eye saccade. Thus the central command, responsible for coordinated eye-head movements, is liable to exibit distinctive patterns depending on the experimental conditions. Both eyes and head movements in the same direction could be linked centrally for functional purposes. Comparable observations in man are described in the literature (Stroud and Burde (1977)). In view of the direction of the induced perceptual and motor effects, and the fact that the vibrated muscles behave as if they were stretched, extraocular proprioception can be considered as mainly involved in the directional transport program for both the eyes and head and, should the occasion arise, for the whole body.

Neural structures liable to control such functional coupling can be sought at various levels of the Central Nervous System. The Superior Colliculus is known to be involved in the control of eye and head movements, which can be associated or otherwise depending on the region of stimulation (Roucoux and Crommelink (1980)). In addition, it receives afferents from the extraocular muscles (Battini, Buisseret and Kado (1974)). Moreover the cerebellum, in particular the vermis and the vestibulo cerebellum, rely heavily on eye movement control especially on smooth pursuit control. Unilateral or total cerebellectomy cause in monkeys severe deficits, and even complete incompetence, in the pursuit of a moving target (Westheimer and Blair (1974); Baloh, Konrad and Honrubia (1975)). The same effects has been observed in human subjects with cerebellar atrophy (Nemet and Ron (1977)).

Furthermore, the eye-head directional coupling involving an adaptive modification of the gain of vestibulo ocular and vestibulo collic reflexes, might be controlled by some part of the pontine and mesencephalic reticular formation (Baker and Berthoz (1977); Berthoz, this volume). Such changes in "neural stategies" depending on the experimental context might support our results. The fact that the same extraocular proprioceptive message may be assigned to the coding of either the eye, head, trunk or whole body position is particularly noteworthy. In addition, proprioceptive signals from dorsal neck and extraocular muscles have been found to converge together with visual and vestibular inputs in the frontal regions of the cat's brain (Dubrovsky and Barbas (1977)). The latter point is worth noting in connection with the assumed involvement of these regions in a higher control of some particular aspects of spatially oriented behavior. Finally, the reported postural effects become important in relation to the fact that extraocular afferent projections to both vestibular nuclear complex and some reticular nuclei have been recently demonstrated in cat (Ashton, Body, Donaldson and Milleret (1985)), but also that the sensorimotor integrative properties of these structures are now established (Xerri, Barthelemy, Borel and Lacour (1985)).

In conclusion, our results show that it is possible to experimentally manipulate extraocular proprioception in man. Moreover, these data suggest that the extaretinal proprioceptive inflow may play an even more important part than that of the classically recognized outflow. Such extraocular proprioceptive signals are able to give rise to conscious kinaesthetic sensations of the head, trunk and whole body, and thus to contribute to the coding of egocentric references involved in spatial information processing. Finally, since vibration of neck muscles can be used to produce similar kinaesthetic and motor effects, preliminary tests with combined eye and neck vibrations are very promising.

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EYE MOVEMENTS: From Physiology to Cognition
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SPATIAL CODING OF VOLUNTARY SACCADES IN MAN

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Three experiments are described in which human subjects must direct the gaze to a previously memorized point in visual space after the initial position of the eye has been displaced voluntarily. In Experiment 1 and 2 the visual target is defined as a point on the retina, while in Experiment 3 it is defined as a position of the eye in the orbit. In Experiment 1 and 3 the voluntary movement away from the initial position is a saccade, and in experiment 2 it is a smooth pursuit. The results are in agreement with the hypothesis that the position of visual targets is coded in a frame of reference based in external space. It is suggested that positional information from retinal error inflow and corollary discharge outflow can be both compounded and called upon interchangeably.

INTRODUCTION

In principle, moving the gaze to a point in space where interesting visual information appears might be achieved with a simple strategy which only presupposes plausible physiological mechanisms. In fact, the location of the distal stimulus is uniquely mapped, via the optical system of the eye, onto a specific retinal location. If one admits that the retinal and collicular circuitry can accurately code the vector from the fovea to the proximal stimulus, (Cynader and Berman (1972) ; Schiller and Stryker (1972)), the correct saccade to the target can be planned by transcoding this perceptual vector in terms of motor commands to the extraocular muscles (Robinson (1972)). This idea, sometimes referred to as the "retinocentric coding hypothesis", is appealingly simple inasmuch as it does not presuppose the necessity for the oculomotor system to have access to whatever information is available on the initial position of the gaze in space, or even on the position of the eye in the orbit. Indeed, formal models of target-directed saccades based on this hypothesis have been proposed early on in the literature (Young and Stark (1963) ; Robinson (1973)).

A number of objections can, however, be levelled against the retinocentric hypothesis, the most devastating of them being that if the head moves before the completion of the saccade, the motor vector computed on the sole basis of visual information cannot possibly compensate for the resulting translation of the visual field. Moreover, the displacement resulting from a given pattern of motor commands depends critically on the initial position of the eyeball in the orbit (Robinson (1975a)). Thus, it is unlikely that the saccadic motor plan neglects completely all types of extraretinal information. Theoretical considerations (Robinson (1975b)), clinical data (Zee, Optican, Cook, Robinson and Engel (1976)), and double-step experiments (Hallet and Lightstone (1976a, 1976b)) all point to the conclusion that in fact saccadic planning depends critically on the availability of accurate, real-time information on the position of the eye in the orbit. Considering that on many occasions eyes, head and body move simultaneously, it certainly makes more sense to suppose that the position of visual targets is coded in an external frame of reference which is unaffected by such movements (the so-called "spatial coding hypothesis" (Robinson (1975b)). Direct evidence in favor of this hypothesis has recently been presented by Mays and Sparks (1980, 1983) who report that if the direction of the gaze is artificially displaced from the original position during the latent period of a target-directed saccade, the correct final position is nevertheless attained. This finding is only explicable with the notion that retinal and extraretinal sources of geometric information are compounded to provide a space-based system of coordinates for locating visual targets. Two sources of extraretinal information can be invoked, proprioceptive inputs from the extraocular muscles and efferent copy from the commands themselves. However, recent results from a deafferented preparation (Guthrie, Porter and Sparks (1983)) suggest that the retinal signal is only compounded with the internally generated representation of the eye position.

The aim of this report is threefold. First we want to replicate the findings of Mays and Sparks in what we consider a more natural experimental condition. It is in fact open to question whether eliciting saccades by electrical stimulation of the colliculus represents for the motor system a condition that it is adapted to cope with. The paradigm proposed in this report is much closer to real-life operating conditions and can be easily implemented in man. Our second aim is to verify the hypothesis that current eye position can be continuously updated also during smooth pursuit displacements. If so, the results of Guthrie, Porter and Sparks (1983) would suggest that efferent information is not only generated by saccadic commands, but by graded motor outputs as well. Finally we will investigate in further detail the role of retinal information in the accurate location of spatial targets. More specifically, having admitted that visual information alone is not in general sufficient for directing the gaze to a particular spatial location, we will address the question of whether such information is actually necessary under all conditions.

METHODS

Subjects

Six subjects (4 males, 2 females) participated in the experiments being payed for their services. They all had normal or corrected-to-normal vision.

Visual display and task

Experiments were run in a totally dark room. Subjects sat within the eye movement recording apparatus with their head immobilized by a biteboard and a forehead brace. The visual display was provided by a HP 1321A, large screen (35.6 by 30.5 cm) oscilloscope driven by the DAC output of the computer. Luminance of the trace (aluminized P31 phosphor) was also controlled via the z-axis input. The distance between the subject's eye and the screen was 57 cm. A 2 mm red LED placed at the center of the screen provided a fixation point in the straight-ahead direction. Point-like visual targets could appear in one among eight symmetrical locations at 10 degrees from the fixation point. In all three experiments to be reported a trial begins with a brief auditory stimulus and comprises four phases : fixate the LED at the center of the field, localize a first spatial location (T1) randomly chosen among the eight possible ones, move to a different random location (T2) and, from there, make a final saccade in total darkness to where T1 had been presented. Subjects were informed neither of the experimental design, nor of the purpose of the experiment. Upon subsequent questioning, none of them was able to indicate whether or not a fixed set of simuli had been used. A complete session comprised 64 trials corresponding to all possible pairings of first and second location. Each subject participated in three sessions spaced by at least one week. The following experimental paradigms were used in the three successive sessions.

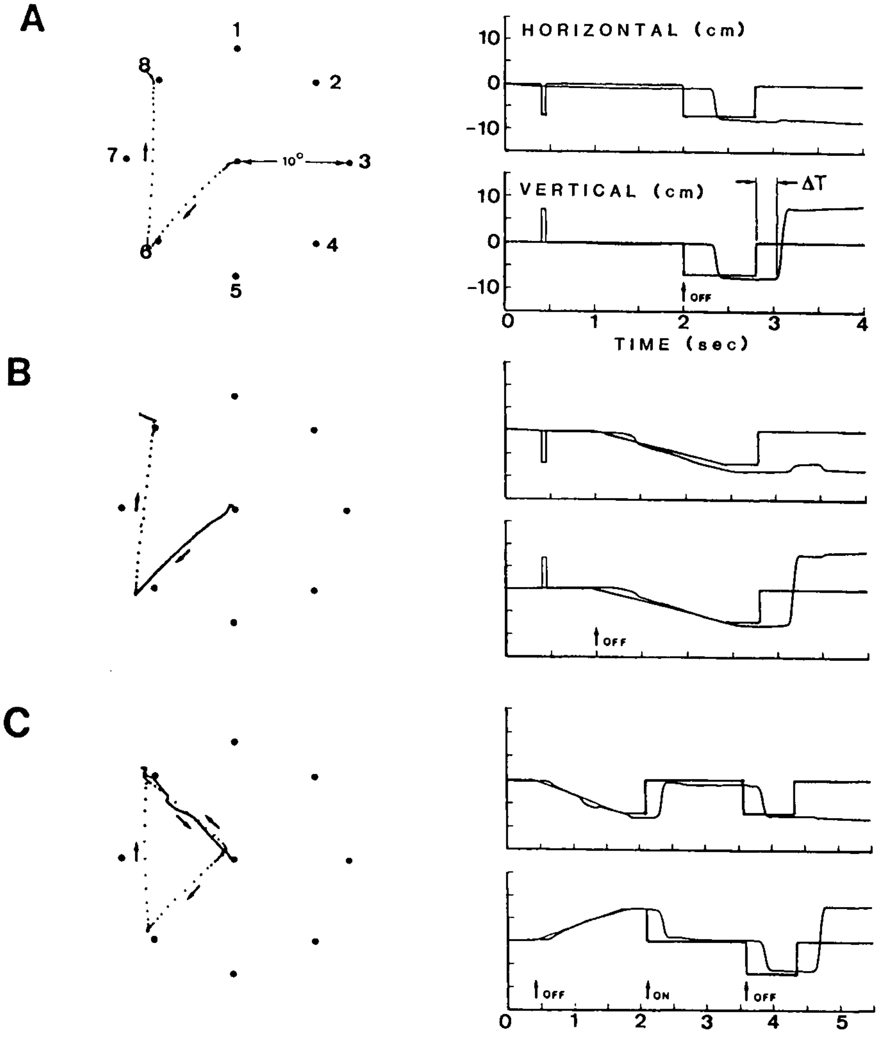

Figure 1.

Description of the experimental paradigms. On the left, two-dimensional display of the eight locations on the screen and of representative trajectories of the gaze in the three experimental conditions. On the right, the time course of the horizontal and vertical components of the eye displacements shown on the left is superimposed on a schematic representation of the target position.

A : After localizing visually the position T1 (8 in this example), the subject makes a saccade to a second location T2 (6 in this example). As soon as this stimulus is turned off, he/she tries to reach with a saccade in total darkness the first location T1.

B : Same as A, but the position T2 is reached with a smooth pursuit.

C : Position T1 is reached with a smooth pursuit. After a second fixation of the center, the trial continues as in A.

Notice that in the three situations, the position of T1 must be memorized for the same amount of time (2350 msec).

Experiment 1 (Figure 1A) - While the subject keeps the gaze on the fixation point, a brief (50 msec) spot appears in one of the peripheral locations (T1). 1550 msec thereafter, the fixation point is turned off and a second location (T2) is simultaneously selected by the spot which stays on for 800 msec. The subject is requested to fovealize the spot wih a saccade until it disappears, leaving a totally blank screen. Then, the subject must try and reach with a saccade the first position T1 and remain there until an auditory stimulus signals the end of the trial.

Experiment 2 (Figure 1B) - The first two phases of the experiment are identical to those of Experiment 1. However, when the fixation point is turned off, the subject must follow the spot with a smooth pursuit. This drives the gaze at 7.14 degrees/sec from the center to the selected location T2 and it remains there for 400 msec. As soon as the driving spot disappears leaving a blank screen, the subject must also in this case try to localize the initial position T1 with a saccade and remain there till the end of the trial.

Experiment 3 (Figure 1C) - After an initial 400 msec fixation phase, the subject must smoothly follow the spot from the center to the first position T1 and remain there for 400 msec. When the stimulus is turned off, the fixation point reappears and the subject must come back to it, maintaining the fixation for 1550 msec. Thereafter, the trial continues as in Experiment 1.

Eye movement recording and data analysis

Angular position of the gaze with respect to head and space was measured by the scleral search-coil technique (Collewijn, van der Mark and Jansen (1975) ; Robinson (1963)). A calibration always preceded each experimental session. Twenty-five locations on the screen, arranged in a 5 by 5 square array and spaced by 5 degrees were sequentially indicated by a spot that the subject was requested to fixate for 5 seconds. The computer then calculated the parameters of a two-dimensional power series mapping of the plane into itself that minimizes the quadratic error between the measured and the actual coordinates of the screen-based matrix. This optimal mapping was finally applied to the raw experimental data. With this procedure the absolute position of the gaze on the display could be determined to within 2 mm. Because the small-angle approximation is extremely accurate in this case results will however be presented in the equivalent angular units.

RESULTS

According to the experimental plan, each subject in a given experimental condition provided eight independent estimates of each location T1, one for every position of the intermediate target T2 (for reasons of symmetry, trials in which T1 is diametrically opposed to T2 were repeated twice). Individual estimates of the accuracy with which localization is possible in every condition are provided by the spatial distribution of the final fixations that, in total darkness, subjects make on the presumed location of T1. Figure 2A,B,C illustrates the results in one subject for the three experimental conditions. For the sake of clarity, we have chosen a subject who was rather accurate both in terms of the average mislocation of the target T1 and of the spatial dispersion of the fixations. Indeed, significant differences exist among subjects for both these two measures of performance. However, the point of the figure that is relevant to the issue discussed here is not the absolute accuracy of the localization, but rather the comparison among the three experimental conditions and, in this respect, the results shown are quite typical. A two-way analysis of variance (8 locations x 3 experimental treatments) was performed both on the distance of the average fixation from T1 and the scatter of the fixation distribution measured by the surface of the confidence ellipses. No significant difference emerged in either case (F(2,10) = 2.80 and F(2,10) = 2.98 respectively) among experimental conditions.

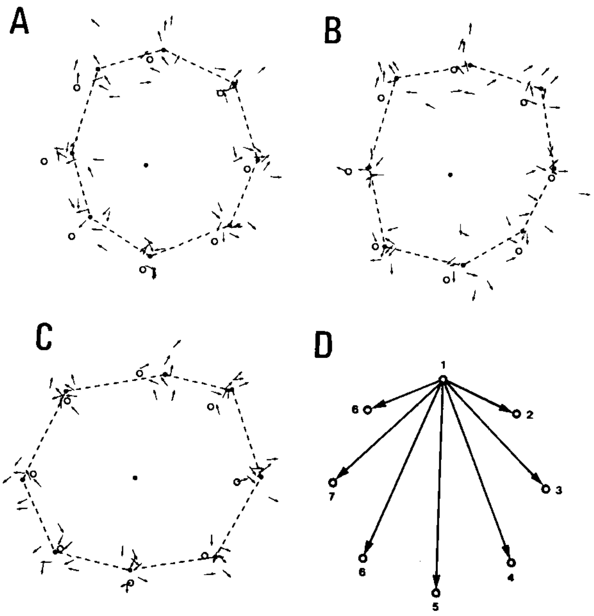

Figure 2.

Distribution of fixations on the invisible target. A,B,C, example in one subject of the distribution of final fixations on T1 in the three experimental conditions. Each arrowhead marks the endpoint of the saccade from T2 to T1 and the direction of the arrows indicate the target from which the movement originates. Dots connected by dashed lines represent the center of gravity of the distribution and unfilled circles indicate the actual position of the target T1.

D : The diagram shows how saccades originating from one point can have 7 different directions and 4 possible amplitudes. Since there are two possible orientations for each direction, and considering the extra direction not represented in the diagram (7-3) the experiments covered altogether 16 different orientations.

A more detailed comparison of the performances in the three experimental conditions can be obtained by breaking down the set of all localizing saccades in each condition according to their direction and amplitude. As shown diagrammatically in Figure 2D, there are 16 possible directions (twice the number of distinct orientations) and four possible amplitudes (7.65, 14.14, 18.48 and 20 cm). The accuracy with which subjects locate the invisible target T1 can then be measured by comparing the theoretical vector T2 T1 with the final saccade leading to the presumed location. Statistical analysis demonstrates that both amplitude and direction errors are independent of the intended saccade amplitude. Instead, they are significantly correlated with the intended saccade direction. In particular, direction errors are larger for oblique movements than for horizontal and vertical ones. At any rate, errors seldomly exceed 10 degrees and, more importantly, their distribution across orientation does not depend on the experimental condition. This is best appreciated in Figure 3 which displays the relation between theoretical and actual values of both amplitude and direction of the localizing saccade in the three experiments. The scatter of data points in both types of regression plots is mostly due to the fact of pooling the results of all subjects, and does not differ significantly across subjects. The visual impression that amplitudes are less accurately programmed than direction is largely a consequence of the scales involved.

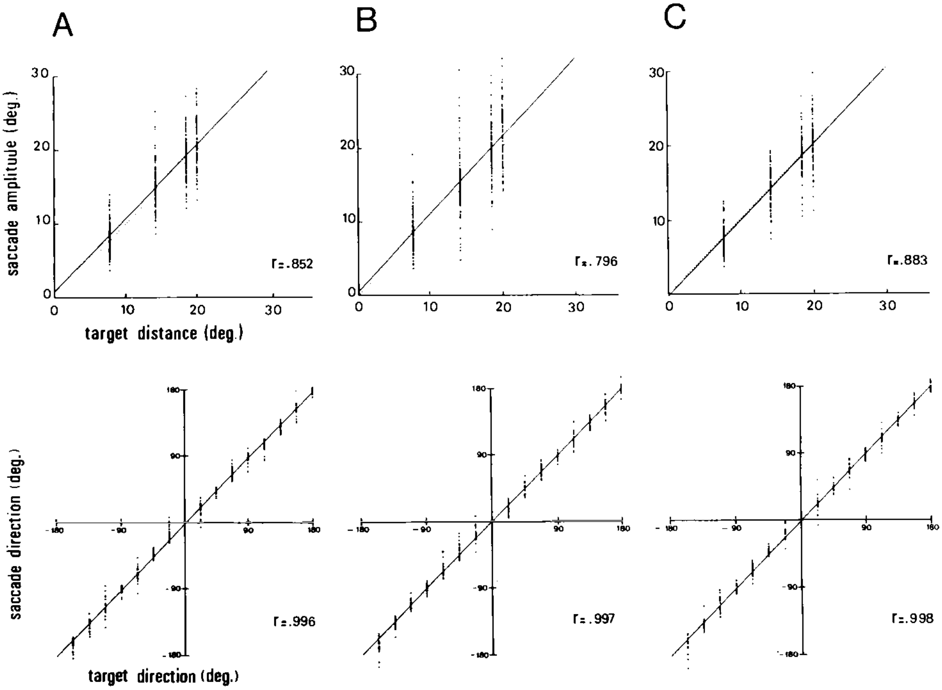

Figure 3.

Correlation analysis. Plots in A, B, and C summarize the results from the three experiments.

Upper plots : relation between the theoretical distance from T2 to T1 (abscissa) and the actual amplitude of the localizing saccade (ordinate).

Lower plots : Relation between the theoretical direction of the vector T2 T1 (abscissa) and the direction of the localizing saccade (ordinate).

Data for all subjects. Lines through the data points are linear regressions. Dotted lines indicate the ideal regression.

Figure 4 demonstrates this point on the basis of the results in two subjects. Each diagram in this figure represents in polar coordinates the joint variation of direction and amplitude errors of the final localizing saccade for each of the 16 possible directions. The radius of the reference circle is 10 degrees and its circumference is the locus of all saccades whose amplitude is equal to the distance between T2 and T1 (no amplitude error). Ticks on the circumference indicate the 16 theoretical directions. The variability in both amplitude and direction are measured by the two orthogonal standard deviations around the means. For each direction, four saccades with different amplitudes are averaged. Thus, the fact that the variability of amplitude errors is small (about 2 degrees across subjects) demonstrates that these errors are almost constant and independent of the saccade amplitude. The figure illustrates in further detail the type of individual differences observed in our experiments. Subjects S1 and S2 where actually selected to illustrate the case of extreme undershooting and overshooting in the planning of the final saccade. However, over and above these differences, the data provide a strong confirmation that no significant difference exists in individual performances across experimental conditions. Finally, the polar diagrams illustrate the systematic (but idiosyncratic) distortions of the perceived location of the targets that were observed in all subjects.

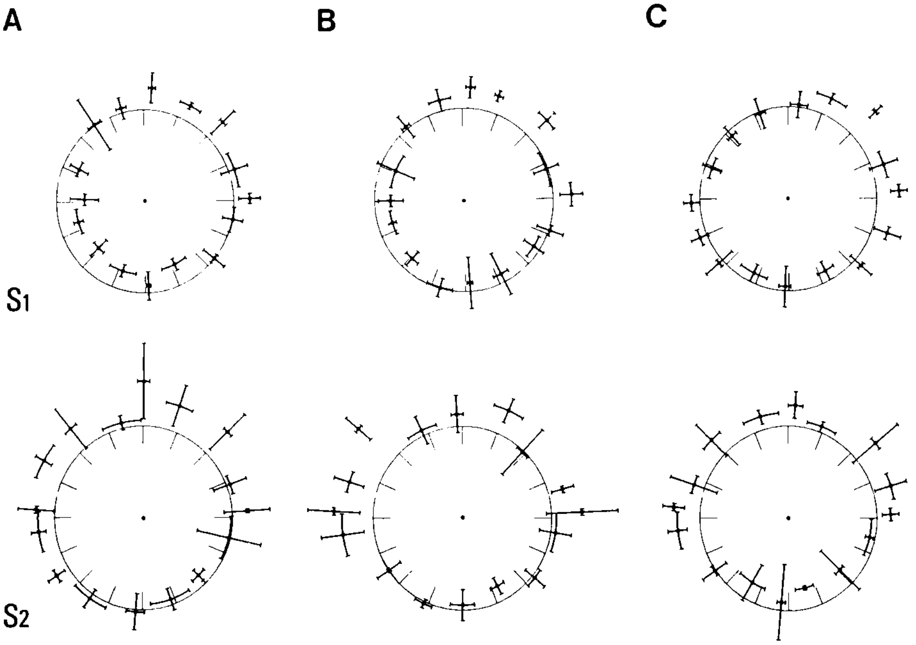

Figure 4.
Amplitude and direction error as a function of direction. Polar diagrams of the covariation of amplitude and direction errors for each of the 16 possible directions of the vector T2 T1. The circumference is the locus of all saccades with no amplitude error. Points within and outside the circumference correspond to undershoots and overshoots respectively. The scale is provided by the radius of the circle which is set to 10 degrees. Data points represent the average errors over the four saccades made by each subject in the indicated direction. Orthogonal bars encompass 2 standard deviations. Data in two subjects (S1 and S2).

DISCUSSION

Experiment 1 has demonstrated that the gaze can be directed to a briefly presented visual target even if the original viewpoint is changed between stimulus offset and saccade onset. While the localization of the invisible target under these conditions is not as accurate as in the usual one-step situation, this result is in keeping with the hypothesis set forth by several authors that retinal inputs are combined with extraretinal position information to provide the oculomotor system with an invariant spatial coding of visual stimuli. We actually maintain that, on several counts, the results improve on the supporting experimental evidence recently supplied by Mays, Sparks and coworkers (cf. Introduction). To begin with, end-point invariance is demonstrated in a far less contrived experimental situation. Both saccades from the fixation point to T2, and from T2 to T1 are normal movements, voluntarily triggered by the subject. The interval between saccades is relatively long (about 800 msec.). Thus, there can be no doubt that the second saccade is planned quite independently of the first one. This in turn rules out the hypothesis that end-point invariance in eye movements is achieved via a stiffness-setting mechanism as it has been suggested for other body segments (Feldman (1966)) and leaves the vectorial composition hypothesis as the only viable one. Notice that the intersaccadic latencies typically observed when the first saccade is electrically stimulated (Mays and Sparks (1980, 1983) ; Guthrie, Porter and Sparks (1983)) are intriguingly short (20 to 60 msec) for such a composition to take place. However, similar short latencies have also been documented in the spontaneous correction of goal-directed saccades (Viviani and Swensson (1982)). Finally, since both intermediate (T2) and final (T1) targets are precisely specified, it is possible to address the question of whether errors of localization are due to perceptual coding or motor commands (Viviani and Velay, in preparation).

Having confirmed that extraretinal information must necessarily come into play in the saccadic capture of visual targets, the question then arises of the nature of this information. The results of experiment 2 bear directly on this issue. Two putative sources of position sense are classically considered (Skavenski and Steinman (1970) ; Skavenski, Haddad and Steinman (1972)) : proprioceptors in the extraocular muscles and corollary discharge. While the two possibilities are not mutually exclusive, the permanence of end-point invariance after deafferentation (ophthalmic nerve section) led Guthrie, Porter and Sparks (1983) to the conclusion that the corollary discharge associated with the stimulus-induced saccades is the major source of extraretinal information. The only difference between experiment 1 and 2 is that in the latter the gaze is displaced from the original fixation by a smooth pursuit, while in the former the gaze is displaced by a saccade. Thus, if we accept the suggestion of Guthrie, Porter and Sparks, the similarity of the results in the two experiments can be taken to imply that smooth pursuit commands give rise to corollary discharge just as saccades are supposed to do. If so, one would predict that the positional visual information and information provided by corollary discharge be somehow interchangeable. In particular, it should make no difference whether the final target T1 is localized visually or via a smooth pursuit eye movement. Experiment 3 affords precisely a test of this hypothesis. Since no significant difference could be detected between the performance in this experiment and that in the two previous conditions, it follows that the existence of a retinal input is not necessary to memorize the location of the final target. As suggested, different types of positional information can be both compounded and called upon interchangeably.

To conclude in a somewhat speculative vein, we would like to argue that such an apparent interchangeability of positional clues is hardly compatible with too "hardwired" a view of the sensori-motor coordination of eye movements (a view for instance that would emphasize the rigidity and reflex-like nature of collicular interfacing). The data are instead more in keeping with the idea of a two-level hierarchical structure, where the lower level comprises an array of mutually independent sensory mechanisms, each measuring a different type of positional clues, and the upper, computational level marshals amodal information from the bottom to conjure up the desired spatial coordinates. As long as the head is fixed, spatial and cephalocentric coordinates coincide and only eye position clues are needed. However, the same general scheme can be generalized to include the possibility of head movements, by adding the vestibular and neck proprioceptive inputs to the array of sensory modules in the lower level.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

DOES THE SACCADIC SYSTEM CONTROL AMPLITUDES OR FINAL POSITIONS ?

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The starting positions of different saccades evoked from the same initial fixation target can vary by as much as 30 min of arc. These discrepancies cannot be accounted for by head movement artifacts. When the experimental conditions are stable, the saccadic amplitude is adjusted to take account of the initial fixation error, and the eye reaches the correct final position in the orbit. This effect is more conspicuous at small stimulus step sizes, where the initial error forms a significant part of the movement. Furthermore, this amplitude compensation is observed even when a drift occurs late in the latent period.

INTRODUCTION

Conventionally, the saccadic response to a jump of a fixation target is characterized by specifying the amplitude of the movement. However, bearing in mind the function of saccades, namely shifting the line of sight to a new object of interest in the visual periphery, the measurement of amplitudes may actually not be appropriate and can furnish misleading results. An example of such a case is shown in Fig 1*A*. Both saccades are seen to reach the same level, the angle of gaze corresponding to the new target; however, the starting positions of the two responses are very different. If one were now to calculate their amplitudes one movement would appear to be too large, the saccade seeming to over-shoot, whereas both responses are in fact correct, reaching the desired goal. It is thus not always sufficient to consider only the amplitude when studying the metrics of saccades.

The stereotyped trajectory enables one to describe the metrics of a saccade in terms of a few parameters: an average during the pre-saccadic fixation period determines the ***initial position***, the mean post-saccadic reading specifies the ***final position***, and the difference between these two values defines the ***amplitude*** of the saccade (Fig. 1*B*). The extreme stability during fixation implies that the movement is very precisely controlled and suggests that small deviations are functionally significant: they must reflect the internal operation of the saccadic system. With the advent of modern recording techniques it has become possible to exploit this feature fully. The final positions of the two saccades shown in Fig. 1*B* differ by only 5 min of arc, yet the separation between the two levels is clearly distinguishable, demonstrating both the precision of the movement and the resolution of the transduction mechanism. It should be pointed out, though, that the responses may be by no means accurate; rather, each time the saccadic system precisely enacts its own internal goal.

Although the line of sight is confined to a narrow range during fixations (Ditchburn, 1973), as also seen in Fig. 1, the eye positions in the orbit can vary considerably when an observer repeatedly fixates the same stimulus (c.f. Snodderly & Kurtz, 1985), even when the head position is adequately controlled.

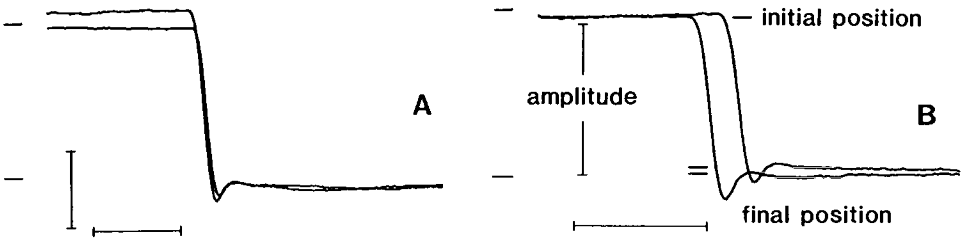

Figure 1
Trajectories of saccades. A: The amplitudes of the two responses differ, but both movements accurately reach the target. B: The parameters defining the metrics of a saccade are shown. Note, a gap of 5 min of arc is clearly resolved. (Calibrated levels for 0 and 2 deg; time scale: 100 msec; vertical scale: 1 deg)

Given the variability in the initial positions, the question then arises how the saccadic system deals with such errors. For a population of responses it is found that the resulting movement does not follow the stimulus step amplitude but that the eye reaches the correct final position corresponding to the direction of the target.

METHODS

Horizontal eye movements were recorded using a photo-electric method. Small spots of light, presented on a CRO display, were viewed monocularly at a distance of 57 cm. Their position was stable within an equivalent angle of 1 min of arc. The subjects were fully adapted to the prevailing luminance levels, and their heads were clamped with the aid of a bite bar and a head rest. Any residual head movements were monitored with a marker taped over the occluded eye and placed in front of a transducer identical to that for measuring eye positions. Both sensors could be shifted together sideways and the gain in the two channels was equilibrated. The head trace was thus calibrated in terms of equivalent eye movements.

An experimental session was made up of a sequence of refixation trials: while the experimental subject fixated the stimulus spot, the stability of the eye position signal was monitored on-line to define a calibration point. Three positions were tested: -10 deg, left; the primary position; and +1 deg, right. The eye signal was analysed over a stable stretch of 100 to 200 msec on either side of the dominant jump shifting the direction of gaze from one calibration position to the other. Only the primary saccades were analysed and a very few aberrant responses were discarded.

Calibrating the output of the photo-electric transducer in terms of absolute eye positions is extremely difficult, as the signal is very sensitive to head movements (Findlay, 1969). However, by monitoring the head movements it is possible to correct the results for the major source of perturbation. The interaction between the head and the eye data can in general be adequately described by an additive, linear-regression noise model, where the recorded eye position is the sum of the true orientation of the eye and a noise term which is a linear function of the head signal (Fig. 2). The calibration curve was checked periodically during a session using a pursuit task, and the non-linearity of these records reveals that they are vertically displaced.

Thus one now needs only to anchor the calibration curve in order to calculate the absolute d.c. level. This is achieved by using the head data. The initial calibration of the head trace, which was performed by shifting both transducers simultaneously as explained above, is confirmed in two ways. Firstly, the magnitude of the characteristic waves introduced into the eye signal due to head movements (Fig. 2*A*) provides a natural method of comparing the relative gains in the two channels. Similarly, the regression of the averaged calibration values against their corresponding head means (Fig. 2*C*) specifies the global relationship between the two channels over longer stretches of time (the correlation coefficients are around .95). The results of all three procedures are consistent with each other. Furthermore, the slopes of the head vs. eye regressions for different test positions agree very well, corroborating the assumption that the response characteristic of the eye movement transducer remains constant.

RESULTS

Fixational variability

While fixating a small spot of light one can encounter several different patterns of eye movements. In some cases the direction of gaze lies within 5 to 10 min of arc from the stimulus, and the fixation mechanism maintains the position of the eye within very confined limits. Fig. 2*A* shows the output of the two transducers for a fixation at the primary line of sight, and to facilitate a comparison between the two channels the two traces have been drawn on the same scale. The total range during the 3 second period extends over less than 10 min of arc. Furthermore, the bumps in the eye signal can often be attributed to corresponding head movements; thus the true eye position over the entire span seems to be extremely constant. Frequently, however, the catching movements do not centre the target exactly on the fovea and the initial fixation error is corrected by slow drifts. In Fig 2*B*, for example, the eye is seen to move slowly over a distance corresponding to about 20 min of arc towards the correct position, as established by the calibration procedure.

Nevertheless, sometimes such errors are left uncorrected, and the stability of the line of sight suggests that these eccentric fixations form a deliberate

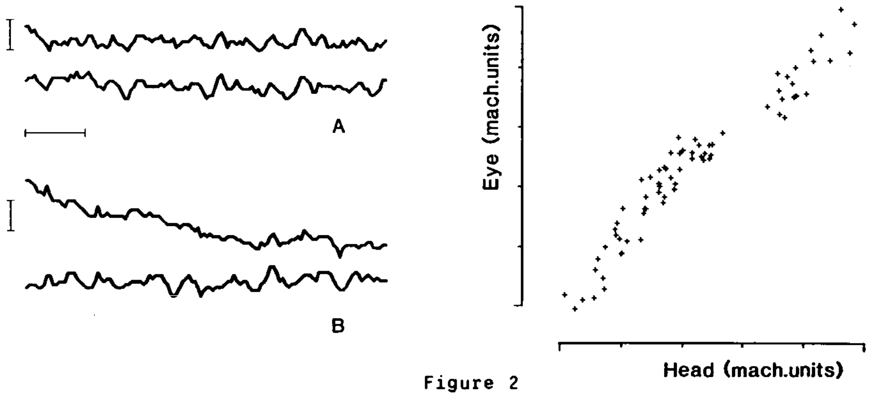

Figure 2
Effect of head movements on eye position signal. A. Stable fixation, with corresponding bumps in both records. B. Fixation preceded by slow drift (Top trace: eye signal, below head movements; vertical bar: 10 min of arc; time scale: 500 msec). C. Long term correlation between averaged head vs. eye samples.

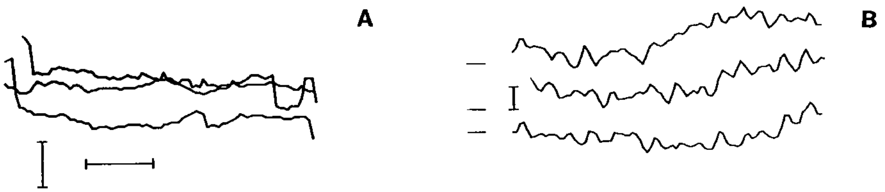

Figure 3
The central fixations of three consecutive trials are superimposed, while the corresponding head movement traces (right) are shifted vertically. Note, for each trial the eye trace remains stable, and during one fixation the trace is displaced by 30 min of arc. (Eye and head vertical scales: 30' and 5', respectively; time scale: 750 msec)

policy in the control of gaze. This behaviour is most clearly demonstrated when the experimental conditions are stable and one can use the uncalibrated records directly. In Fig. 3 three fixations with the target straight ahead are superimposed, and the corresponding head traces are depicted, vertically shifted as they are almost identical. For this sequence of three consecutive trials the head movement trace remains stationary over the entire period, with a constant average level and displaying mainly only the typical 4 Hz component (Skavenski, Hansen, Steinman & Winterson, 1979). In addition, the stability is confirmed at the other fixation positions. The records show that, for each trial, the eye stays within a narrow range over the complete period displayed. During two of the trials the levels of the eye signal coincide. However, in the third one the stable fixation is clearly shifted and remains there throughout the whole fixation period.

Amplitude compensation

It might be supposed that the saccadic system still responds with the stimulus amplitude in spite of the varying initial positions. For instance, if the external representation within the retinotopic map is shifted together with the displaced fixation, any error during the initial fixation is carried over as the observer turns to the new target. In this case, one would expect a positive correlation between initial and final positions. Essentially, the saccadic system would be matching the magnitude of the movement to that of the input step. On the other hand, if the final positions are controlled, one would find a negative correlation between the initial positions and the *amplitude* of the movement. For instance, when the eye drifts towards the new target, a positive error for a positive, rightward saccade, then the resulting amplitude needs to be reduced in order to reach the target correctly. Thus any perturbation during the initial fixation will not affect the final position of the movement and the amplitude will be properly adjusted to compensate this error.

To minimize the effect of the motor variability we shall be considering only small saccades to a target step size of one degree. Fig. 4*A* displays a scatter diagram of initial fixation positions against the amplitudes of the following saccade. There is a general tendency for the data points to lie along a line with a slope of -1, but the correlation is in fact not very strong (r=-.45). Although the fixational inaccuracies are quite large relative to the stability of the eye during the pre-saccadic period, the complete range of deviations is actually not very big. On the other hand, even for the one degree steps examined here the motor variability is only a little smaller, and over the course of a long experimental session one finds several refixations that are made up of multiple saccades. Indeed, the general pattern is more apparent if we confine the analysis to trials in which the response was made in a single step (Fig 4*A*: r=-.80). In addition, any calibration errors will further obscure the relationship and increase the residual variance of the correlation. However, the diagram shows that the extreme points lie along the correct axis; thus, when the initial fixation error is large the saccade takes this misalignment into account and compensates the amplitude appropriately. Furthermore, when one selects pairs of consecutive trials one regularly finds trajectories like in Fig. 1*A*. In view of the precision with which the end points of a saccade are defined, such pictures with overlapping final positions are very sensitive to small perturbations and require extremely stable experimental conditions, which are more difficult to maintain over longer stretches of time. On the other hand, the frequent encounter of such examples makes it unlikely that they are merely produced by chance.

Furthermore, it is observed that the movement can still achieve the desired goal even if the fixation error occurs too late for the visual information to be updated and to influence the control of the saccade. For instance, sometimes the eye drifts in the latter part of the latent period (c.f. Kowler & Steinman, 1979). Inspection of such trajectories shows that the movement tends to arrive at the correct position even though the deviation from the central line of sight starts within the latent period and continues all the way until the saccades sets off, as demonstrated in Fig. 4*B*. Because the drift velocities during fixations are rather low the errors encountered in these cases are quite small. But the precision of the movement enables us to see clearly that the system takes account of the drift and compensates the amplitude so that the desired orbital position will be reached.

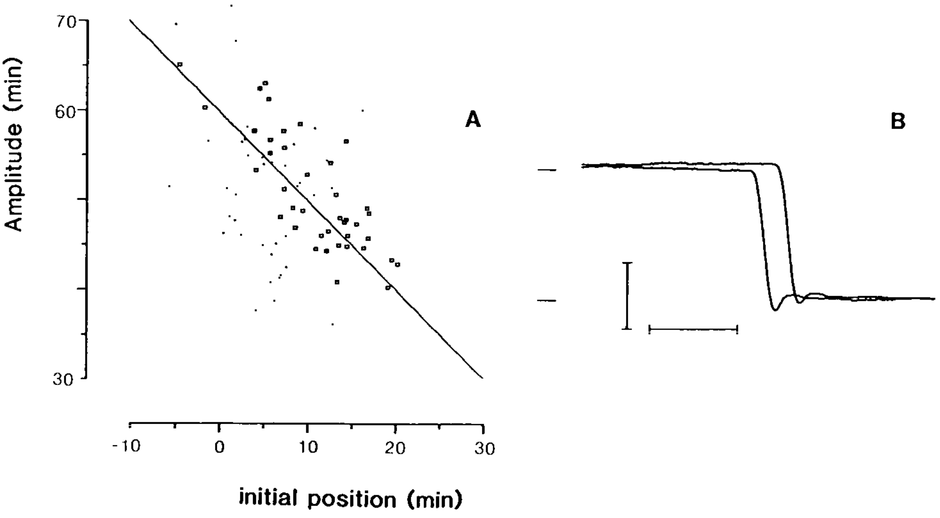

Figure 4
A. Scatter diagram of the initial positions against the amplitudes of saccades to a 1 deg target, with the axis for normometric responses to the correct final position. (all primary saccades: r=-.45, n=78; single step responses, squares: r=-.80; n=40). B. Drift in the latter part of one latent period, but both saccades reaching the same final position. (Markers and scales as in Fig. 1*A*)

DISCUSSION

The observation that the fixation position is not always constant has also been found by other groups using different recording techniques. The fact that the saccadic system takes account of this error confirms that the variations are genuine changes in the eye position. While the fixational inaccuracies can be reliably established, the origin of this variability remains uncertain. In this study the sequence of stimulus presentations was fixed, and the observers seemed to be drifting in anticipation of the next target jump. Indeed, Fig. 4A shows that the majority of eccentric starting points is in the direction of the new target. The short-term stability of the eye position suggests, though, that the direction of gaze is deliberately not aligned with the fixation spot.

The signals of the neural processing may be specified in either a retinotopic, relative or an orbital, absolute frame of reference. With certain assumptions these two alternatives would be expected to act differently. We shall suppose that the displaced fixations are registered by the saccadic system. If then an amplitude command feeds into the circuitry governing the movement, the amplitude of the response would match that of the stimulus step size. A fixation error would be ignored as the internal representation of the external world is shifted with the misalignment, resulting in a positive correlation between initial and final positions. In fact, we find a negative correlation between the initial position and the amplitude of saccades, indicating that it is the final position which is controlled.

The experiments of Sparks & Mays (1983) are often quoted to demonstrate that the saccadic system controls the final position in the orbit. While it may indeed be safe to transfer questions concerning general control principles across species, the interpretation of these results also rests on the assumption that the electrical stimulation of the superior colliculus does not influence the processing of the saccade in preparation and that the activity for the intervening movement does not feed back into the neural circuits holding the pending goal. These problems are avoided here as we are examining normal saccades and only rely on the natural perturbations accompanying this task.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

THE SYSTEMATIC UNDERSHOOT OF SACCADES: A LOCALIZATION OR AN OCULOMOTOR PHENOMENON?

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Using an overlap paradigm to increase the saccadic latency, the undershoot and variability of visually induced saccades has been measured as a function of latency (0.2-0.6 sec) and eccentricity (1-8 deg). The undershoot seems to be caused by a temporal filtering of the visual input (Where-function) and a subject dependent strategy to prevent overshoot above 0.1 deg. Perceptual localization JND has been measured as well for the same eccentricities, durations and subjects. It was considerably smaller than the saccade variability in the same conditions.

INTRODUCTION

Most experiments with visually elicited saccades use the following paradigm: A subject fixates a stimulus, usually a small light dot in a dark field, that suddenly jumps to a new location. The subject is instructed to follow the target and does that by making one or more saccades. Under these conditions, and if the size and direction of the target jump is randomized, the saccade usually undershoots the target, and a correction saccade or smooth movement is necessary in the same direction.

The amount of undershoot found in the literature varies considerably, but most authors agree now at an average value of about 10% (Becker and Fuchs, 1969; Deubel, Wolf and Hauske, 1982; Frost and Pöppel, 1976; Henson, 1979; Prablanc and Jeannerod, 1975). However, Timberlake, Wyman, Skavenski and Steinman (1972) found 30-50% undershoot with small stimulus jumps (0.1-3 deg). The undershoot seems to be a basic built-in property of the saccadic system: if the apparent 90% gain of the saccadic system is corrected artificially, either by an extra stimulus displacement of -10% of the original step during each saccade, or by a contact lens, adaptation occurs quickly: The subject decreases his saccade gain until it once again undershoots by 10% (Deubel, 1984 p. 47; Henson, 1978; McLaughlin, 1967).

To explain the undershoot, two basically different theories exist. The first has been based on the concept of separate systems for the triggering of a saccade (the WHEN-system) and the calculation of its size (the WHERE-system). The where-signal is an internal representation of the stimulus position, which is sampled as soon as the when-system triggers a saccade. The where-signal is supposed to be a delayed and filtered version of the input signal (Becker and Jürgens, 1979; Deubel, 1984 p. 57; Van Gisbergen, Gielen, Cox, Bruijns and Kleine Schaars, 1981). Because of the filtering, a step stimulus will result in an only gradually increasing where-signal, causing saccades with short latency to undershoot the target. Because of the rather small variation in reaction time with single step targets, this concept has mainly been tested with double step stimuli.

The alternative theory explains the average undershoot as the result of a strategy to prevent overshoot. An overshoot would have some kind of penalty for the system.

One such penalty could be an increasing chance of oscillations (instability). Another could be that the subsequent correction saccade latency is longer if it has to be in the direction opposite the primary saccade. This also has not been measured for single step stimuli, but for double steps, with the second step during, or just after the initial saccade. The latency of the corrective saccade depends very much on the stimulus step sizes and timing, but a saccade in a direction very different from the primary saccade is always 20-60 ms later than a correction saccade in a similar direction (Becker and Fuchs, 1969; Becker and Jürgens, 1979; Deubel, 1984 p.41; Henson, 1978; Hou and Fender, 1979; Wheeless, Boynton and Cohen, 1966). Several causes for this longer latency have been suggested: Robinson (1973) and Henson (1978,1979) suggested that a stimulus that stays within the same hemisphere of the brain is facilitated; this theory obviously fails for vertical saccades, where the same phenomenon has been measured. Hou and Fender (1979) presented the theory that it would take time to reverse the role of agonist and antagonist muscles. The latest models of the saccadic system (Becker and Jürgens, 1979; Deubel, 1984) incorporate different channels for different directions. A decision for a corrective saccade will be taken as soon as a channel makes a primary saccade, but must be cancelled, and a new saccade must be triggered if the error turns out to have the wrong sign. Whatever the cause, the longer latency of opposite correction saccades seems to be there. Thus, an explanation for the undershoot could be, that, given an inevitable variability, the system programs a saccade that is too short, to be sure that the probability of an overshoot of the actual saccade is small. If it assumed that the system attempts to keep the overshoot probability smaller than a fixed value, the amount of average undershoot must be a constant proportion of the variability of the saccades (i.e. the standard deviation of the distribution).

Our first experiment has been designed to discriminate between these two hypotheses. The influence of two variables: time and stimulus step size on undershoot has been measured. The second experiment deals with the question where the source of saccadic variability is located: either in the sensory system or the oculomotor system. Assuming that the oculomotor system uses the same input channels for localization as the perceptive system, the localization variability seems an important parameter. Absolute localization is impossible to measure, so we chose an approach in which the difference between two perceptive locations was measured, using a method suggested by Andrews and Miller (1978). Viewing time and location were varied, similar to Exp. 1, and the localization and saccade variability have been compared. Both experiments have been carried out with the same subjects, in a randomized order, during several sessions, to make comparison as valid as possible.

METHODS

Eye movements have been measured with a search coil in a magnetic field (Robinson, 1963; Collewijn, Van der Mark and Jansen, 1975). System resolution was 0.005 deg, accuracy 0.017 deg, measured with an afterimage method (De Bie, 1985). The stimulus consisted of small light squares, 0.03 by 0.03 deg, in a dark field. The average intensity of the squares was about 2 log units above foveal threshold. The subjects viewed the stimulus monocularly, the other eye closed and covered. Three subjects participated in the experiment; one (JB) was experienced and aware of the design and purpose of the experiment. JP and PB were naive paid students. All subjects had normal monocular vision. The experiments were carried out in 16 sessions of 40 minutes for each subject, in a period of 4 weeks. In each session portions of Exp. 1 and 2 were mixed.

Experiment 1

A fixation stimulus was displayed for a random time between 1.5 and 2.5 sec. Then a second, peripheral, dot was displayed simultaneously. After a variable overlap period, the central dot went off. The sequence was concluded after another second, and the fixation stimulus was displayed again. The subjects were instructed to fixate the peripheral dot as soon as the central stimulus was extinguished, as quickly and as accurately as possible. Overlap times of 0, 0.12, 0.25 and 0.5 sec, and locations 1, 2, 4 and 8 deg to the left and to the right were mixed randomly. The number of trials for each position, overlap and subject was 100.

Experiment 2

A stimulus sequence started again with a random period of fixation, lasting between 1.5 and 2.5 sec. Then two peripheral spots flashed on simultaneously, placed on the horizontal axis, almost symmetrically around the fixation spot. The fixation spot was extinguished 0.1 sec before the peripheral spots went off. The subject's task was to keep fixating the central spot and to indicate which of the flashed targets was the most eccentric. The eye movements were monitored during the experiments, and the subjects warned if they made an eye movement to one of the peripheral spots. Flash durations of 0.1, 0.22, 0.35 and 0.6 sec and distances of 1, 2, 4 and 8 deg were used. For each distance and flash duration a set of 5 distance differences was used, that was recalculated once in a while to keep the proportion of answers in each direction between 20 and 80%. The final localization standard deviation was calculated with probit analysis (Finney, 1971), using 20 probability estimations, based on 24 trials each. The distributions were normal in

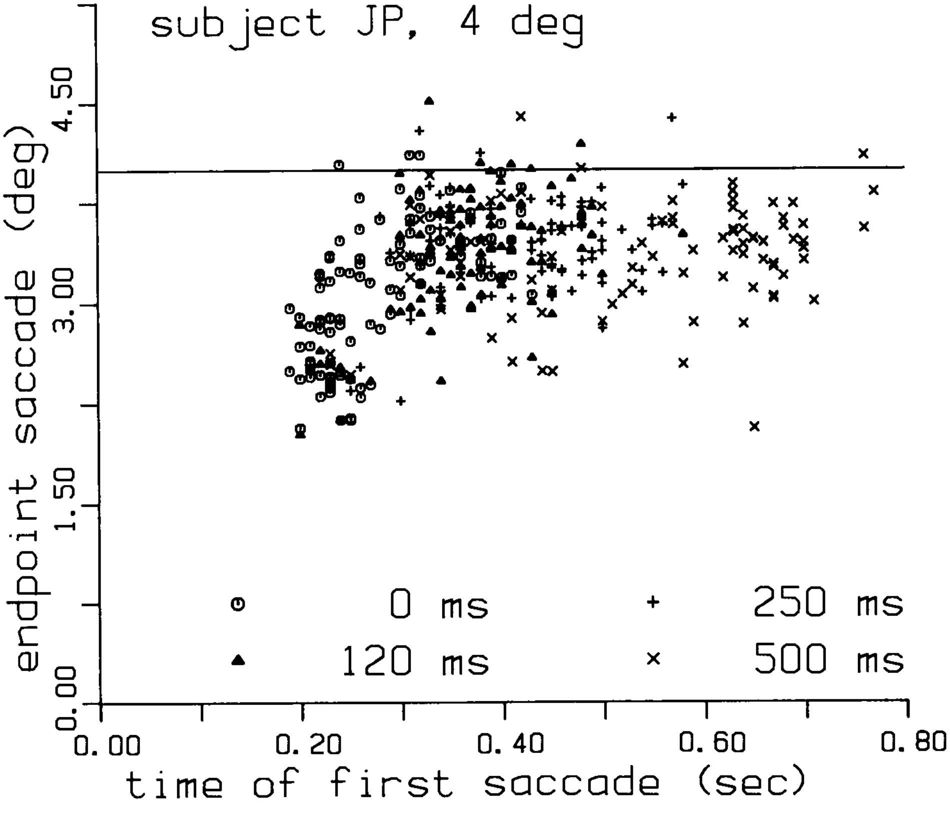

Figure 1
Primary saccade endpoint as a function of latency. Time reference is the moment of peripheral stimulus on-set.

most cases, so that probit analysis is justified. Based on the assumption that the difference judgement is accomplished by the comparison of two independent stochastic variables, each representing the retinal position of one of the two spots, we took as a measure of localization variability the square root of half the difference variance.

RESULTS

Experiment 1

Fig. 1 shows the results of JP, stimulus position 4 deg to the right. The end positions and moments of the primary saccades have been plotted. The time reference is the moment of peripheral stimulus on-set. This subject was disobedient in the sense that he sometimes made saccades to the target when the central stimulus was still on. The trend towards larger saccades with longer latencies is clear. The differences between subjects are large: JB behaves similar to JP, but PB does not show much undershoot at all. Instead, he tends towards overshoot in his later saccades. The differences between leftward and rightward saccades were also considerable, but idiosyncratic. However, saccade size always increased with latency. Therefore, we thought it appropriate to average all subjects and directions, and the result can be seen in Fig. 2. In this figure the time has been divided into 0.1 sec bins, and all saccade endpoints within a bin have been averaged.

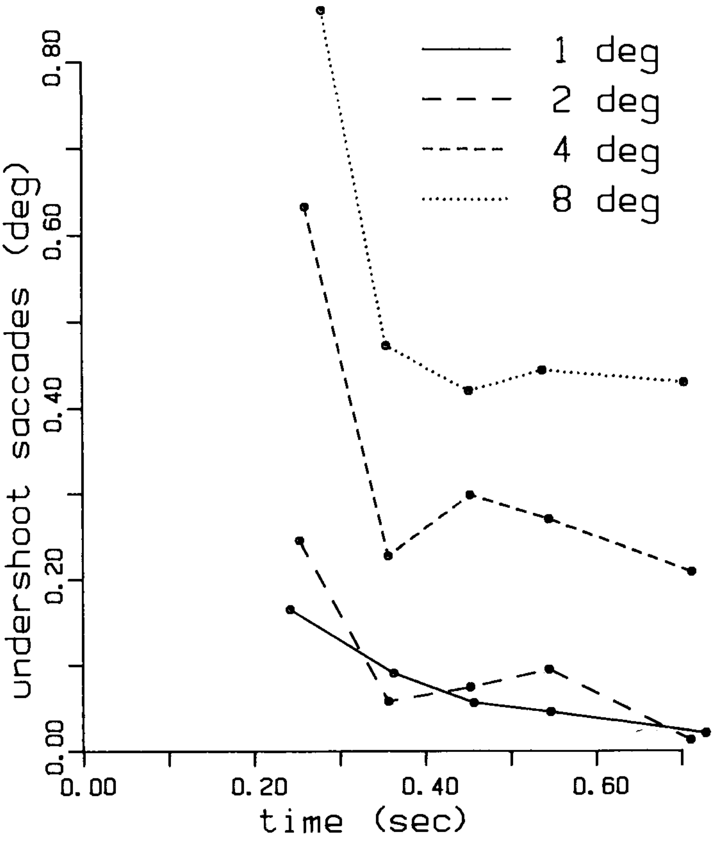

Figure 2
Primary saccade undershoot averaged over subjects. Horizontal bin width 0.1 sec.

The standard deviation of the saccade endpoints has been calculated in the same manner. The intersubject variability was far less than the undershoot variability, less than 20%. The results have been plotted in Fig. 3. The decrease of the standard deviation in time is proportionately less than that of the undershoot. The relative standard deviation decreases as a function of eccentricity, from about 16% at 1 deg to about 8% at 8 deg. It is clear that there is no linear relationship between undershoot and standard deviation.

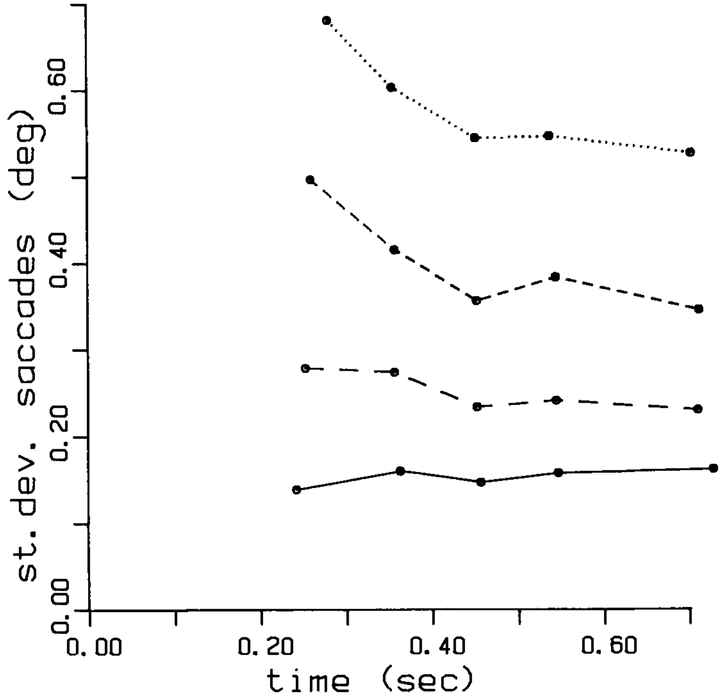

Figure 3
End position standard deviation of primary saccades. Curves from bottom to top: step sizes 1, 2, 4 and 8 deg.

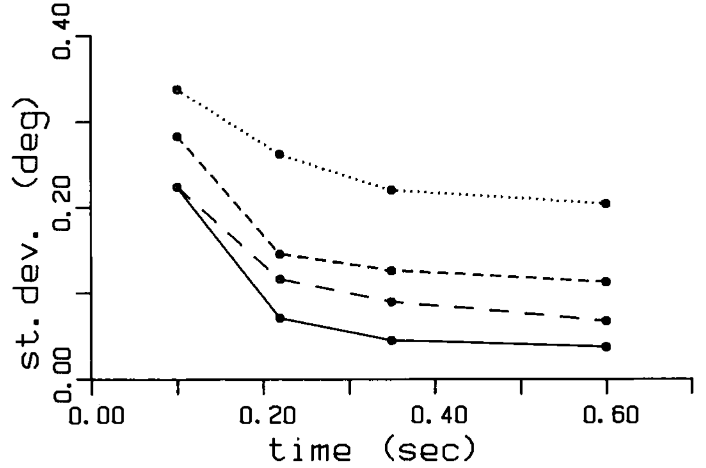

Figure 4
Localization standard deviation as a function of flash duration. From bottom to top: distances 1, 2, 4 and 8 deg.

Experiment 2

The localization standard deviation varied considerably between subjects, a factor 2 was not uncommon. However, the trend was similar in all subjects. The averaged result can be seen in Fig. 4. With decreasing flash duration, the curves seem to converge to 0.3-0.4 deg for all distances, while with longer flashes the relative standard deviation is constant at about 3%. Clearly, the subjects can perform this task better than they can make saccades. There is no direct relationship between localization and saccade variability: the subject that had the highest sacccade standard deviation performed best in the localization task.

DISCUSSION

Experiment 1

Saccadic undershoot as a function of time has never been studied systematically for single step stimuli. The fact that all subjects showed a decreasing undershoot function, i.e. an increasing saccade endpoint function, confirms the theory of a low pass filtered representation of retinal error, the where-function (Deubel, 1984; Van Gisbergen et al., 1981). Until now, this theory has only been confirmed for double step stimuli. The neurological basis for the where-function is not known, but Deubel (1984) suggests a connection with visual temporal transfer functions, that have indeed a similar low pass character (Roufs and Blommaert, 1981).

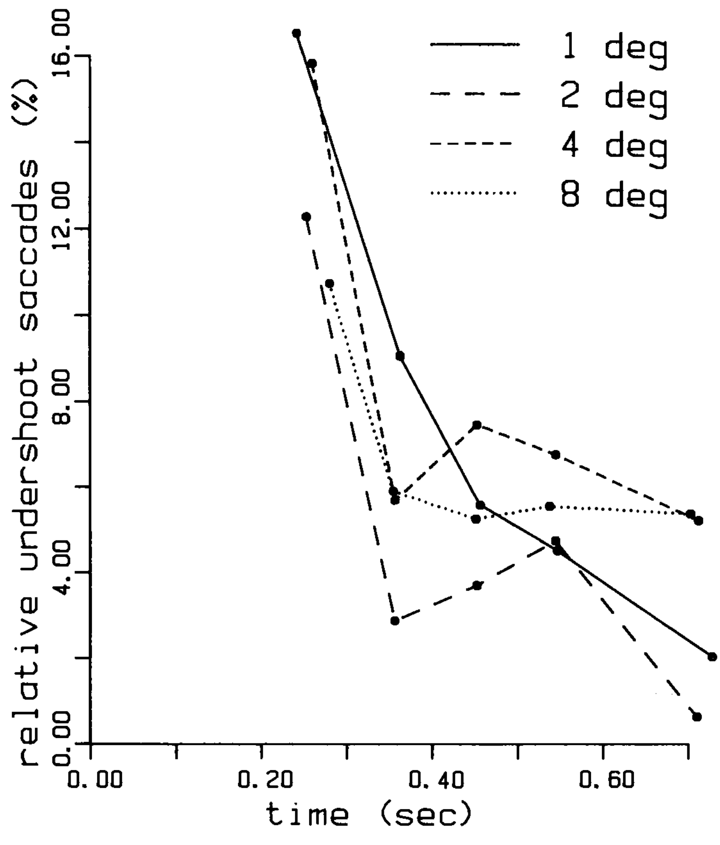

Figure 5
Ratio of primary saccade undershoot and stimulus step size.

The where-function that we found is by no means linear, as a plot of the relative undershoot (Fig. 5) makes clear: the function is less steep in the 0.4 - 0.8 sec period for 8 deg step size than for 1 deg. It seems that there exists a spatial undershoot function, independent of the temporal where-function, that acts as an offset for the where-function. It would be interesting to see if the where-function can be extended towards shorter latencies, for instance in a gap paradigm.

The alternative explanation for the undershoot is that it would be a strategy to prevent overshoot and the penalty of a longer correction saccade latency. This theory predicts the huge intersubject differences that we found (Fig. 6): it is a matter of choice whether to accept overshoot, and be on the avarage closer to the target after the primary saccade, or to undershoot on purpose, making a faster correction saccade possible. A strategy to prevent overshoot does not provide an explanation for an undershoot decreasing with latency, but it does predict a constant ratio of undershoot and variability. This prediction is not borne out: the undershoot function of time is considerably steeper than the standard deviation.

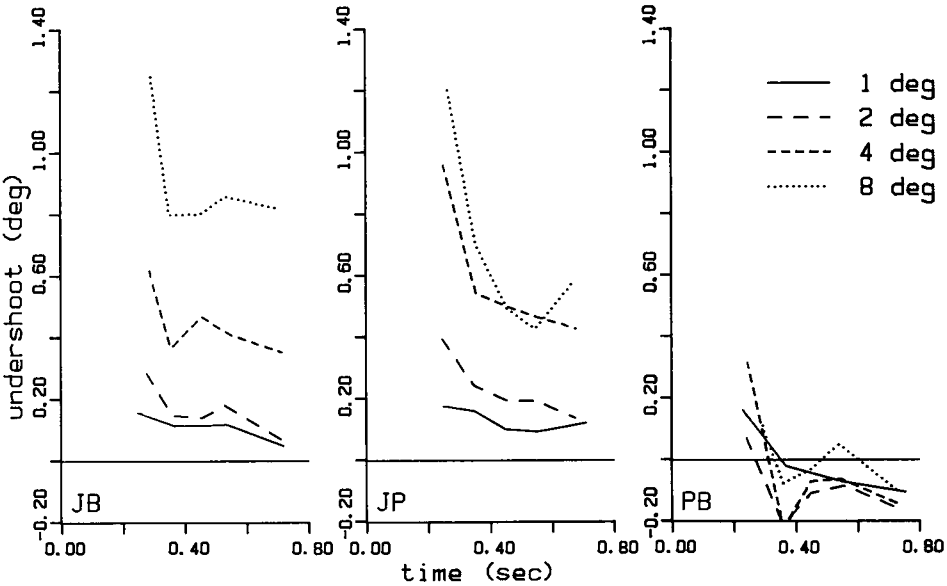

Figure 6
Primary saccade undershoot for the three subjects separately.
Horizontal bin width 0.1 sec.

At first sight, the variability and undershoot functions of eccentricity are different as well (Figures 2 and 3). However, if only saccades with latency above 0.4 sec are considered, they are suprisingly similar (except for the 2 deg stimulus) if only 0.1 deg is added to all undershoots (Fig. 2 is offset by one scale unit). The percentage of saccades that overshoot more than 0.1 deg is the same for all eccentricities (16%). In the light of the overshoot-prevention-theory, this result can be understood if an overshoot of 0.1 deg is accepted by the system as on target. That would, of course, make sense: such a small overshoot is usually not followed by a correction saccade.

Summarizing, our results indicate that the concept of a where-function explains the decrease of undershoot in time. However, the existence of a remaining undershoot for latencies above 0.4 sec, its relationship with the standard deviation, and the intersubject variability suggest a strategy to prevent overshoots larger than 0.1 deg. The two effects seem to add.

Experiment 2

The variability of the saccades is caused by a combination of the variabilities of visual localization, the transformation from retinal to oculomotor coordinates, and the oculomotor system itself. To distinguish between these different causes is very difficult in the intact organism. Our Exp. 2 was designed to separate the localization variability.

The assumption here is that the oculomotor system uses the same input channels as the perceptive system. An experiment of Van Asten and Gielen (This volume) indicates that this is true for localization processing. They compared the dependence of the saccade and the perceptive system on stimulus duration, luminance and colour, and found no difference between them. Our goal was to measure absolute localization precision. However, because of the obvious scaling problem, we had to use a differential method. In our design, the subject had to compare two distances, that were diametric around the center of fixation. We do not believe that the subject could use the symmetry of the stimulus to perform better than expected on the basis of single spot localization: hyper-acuity has not been reported with this stimulus. Also, our own pilot experiments, in which the two distances compared were orthogonal, gave the same results as the experiments with diametric distances. Therefore, we assume that our definition of the standard deviation of localization is indeed a good measure of the localization variability. An alternative approach, in which the JND for locations temporally instead of spatially apart were measured (Matin, Pearce, Matin and Kibler, 1966), was rejected because of the very strong influence of short term memory loss (Matin, Pola, Matin and Picoult, 1981)

The localization variability is considerably smaller than the saccade variability. Also, their functions of space and time do not match. This means that visual localization is not the most important source of saccadic variability. Another indication that localization is not the main error source is an experiment done by Schiller and Stryker (1972). They stimulated the superior colliculus of a rhesus monkey to produce saccades. The colliculus provides a map of retinal and oculomotor space, and is considered to be the location of the transformation from one to the other. Schiller and Stryker measured a saccade size variability of about 15% with repeated stimulation under exactly the same conditions at the same spot. This figure is similar to or larger than visually triggered saccades, suggesting that the main source of variability is located more peripherally.

In summary, perceptual localization variability seems to be a minor factor in the saccadic variability. More important are either the transformation from retinal to oculomotor coordinates, or the oculomotor system itself. However, we cannot be sure that our perceptual localization standard deviation is a good measure of the amount of variability accounted for by the localization process in the saccadic system. Our results can only be a first step towards the understanding of the sources of saccade variability, and more experiments in this field are needed.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

Saccadic Programming With Multiple Targets Under Different Task Conditions

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This study deals with the influence of higher cognitive processes on the so-called averaging (Ottes et al., 1984) or global effect (Findlay, 1982). Using three types of targets consisting of random dot patterns the influence of (1) various task demands, of (2) target location in the visual field and of (3) more than two simultaneously presented stimuli on the global effect was investigated. The results show that the programming of saccades is based on a hierarchical response system dependent on the complexity of stimulation and the task of the observer.

INTRODUCTION

In old fashioned terms, saccades have often been called "voluntary eye movements". But until now we have all realized that it would need a lot of wilfulness to plan the approximately 200,000 saccades which we produce per day. On the other hand saccades can be produced on a purely voluntary basis (for example if somebody asks us to look at a certain spot). The interesting question now is to find out which processing mechanisms are guiding the saccadic system. Especially those researchers who are integrating neurophysiological work with psychophysical experiments tend to assume that there is an automatic mechanism.

In a number of studies done by Coren & Hoenig (1972); Lévy-Schoen (1969); Findlay (1982), Findlay & Crawford (1983) and Ottes, van Gisbergen & Eggermont (1984) an experimental paradigm was used where two visual stimuli were presented simultaneously at different locations in the visual field. The results of these studies support the idea that the visual information used in the production of saccades is severely limited in the capacity for spatial resolution. This leads to a bistable response if the difference in eccentricity or direction of the two stimuli is large. If the difference is under a certain limit an averaging effect is observable, i.e. the resulting saccade falls somewhere near the center of gravity of stimulation. This assumption is supported by results found in electrophysiological studies by Wurtz & Mohler (1976); Wurtz & Albano (1980); Goldberg & Bushnell (1981). Analyses of the responses to double-spot stimuli confirmed a spatial selectivity of the saccadic system in target selection. Becker & Juergens (1979) and Findlay (1981) suggested that two channels are involved in the process of generating saccades. One channel determines the instant at which the saccade is initiated and selects its direction; the second channel determines the saccade amplitude.

Another question concerns the influence of higher cognitive processes on those basic neural mechanisms (Viviani & Swensson, 1982). Findlay (1982) varied in his second experiment the stimulus characteristics by using squares instead of spots as targets. He also varied task demands. Using the same stimulus material, Ss were either instructed to perform a detection task or a comparison task. Findlay's results confirm the "center of gravity" idea of Coren and Hoenig (1972) in a qualitative way, i.e., the landing point of saccades was systematically closer to the near stimulus.

Saccade amplitudes and latencies were influenced by the different tasks. Very unexpectedly the saccade shows a stronger global effect, i.e. falling in between the two targets, in the detection task rather than in the comparison task. Furthermore a difference in saccade latency was found between the tasks.

Along the line of the studies just mentioned we designed an experiment which had a threefold purpose. Using more complex stimulus material we tried to investigate the influence of (1) various task demands on the global effect; of (2) target location in the visual field on the global effect; and of (3) more than two simultaneously presented alternatives.

METHOD

Three Ss took part in the experiment. They were completely naive concerning the purpose of the study.

As stimulus material random dot patterns were used. They had dot densities of either 10% or 80% and were generated by a graphic system and displayed on a CRT. A dot pattern could appear in equidistant positions around a fixation cross at any of eight positions (see Figure 3). The distance between fixation cross and dot pattern was 7 deg of visual angle. Each dot pattern had a side of length about 2 deg.

Three types of targets were used. We had single targets with one dot pattern of either high or low dot density (Figure 1). Then there were double targets with high or low dot density in both patterns (Figure 2) or with a combination of low and high density. As a third target type we used complex stimuli containing eight dot patterns. They were composed of seven low density and one high density pattern or vice versa (Figure 3).

Figure 1: Examples of single targets with one dot pattern of high (left) and low (right) dot density.

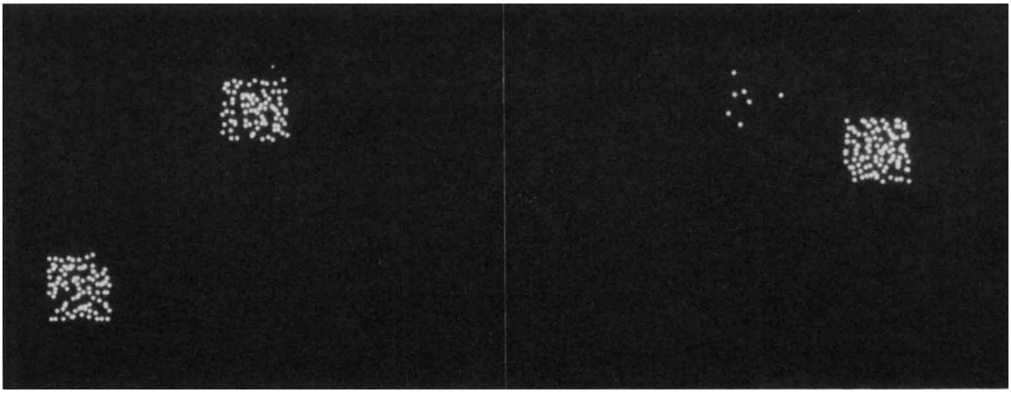

Figure 2: Examples of double targets with high dot density in both patterns (left) and with a combination of low and high dot density (right).

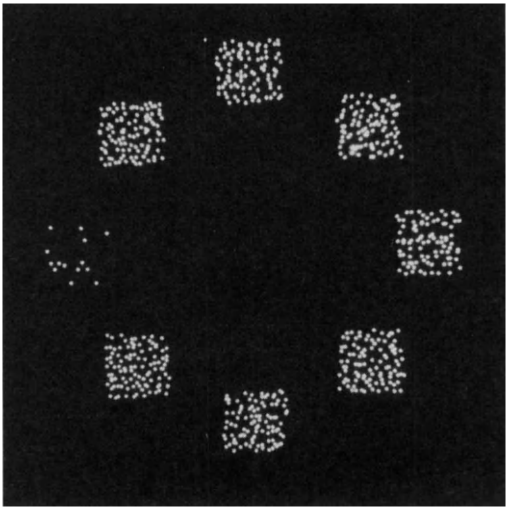

Figure 3: An example of an embedded target composed of seven patterns of high and one pattern of low dot density.

The systematic combination of the eight pattern positions with the other stimulus conditions resulted in a total set of 96 different stimuli. This set was presented several times to the Ss, always in a different random order.

Another independent variable was the instruction given to the S. Each stimulus of the set was preceded by a fixation cross presented in the center of the display for 1 sec. The Ss were constrained to fixate the cross precisely before jumping to the target. The target replaced the fixation cross and appeared for 1 sec. In one instruction condition, called free inspection condition, the Ss were told to fixate the cross first, but got no further instructions where to look next when the target appeared. Under the second instruction condition Ss had to concentrate on the low dot density pattern after having fixated the cross. Under a third instruction the Ss were told to pay attention to the high dot density patterns. During the presentation time of the targets eye movements were recorded by a TV-based corneal reflection device. The sampling rate was 50 Hz.

Under each instruction condition the stimulus set was presented eight times. This resulted in a total of six experimental sessions per S, each lasting one hour.

ANALYSIS

The data (approximately 7000 saccades) were analysed with respect to two dependent variables, the direction of the first saccade and the saccade latencies. The latency is defined by the fixation duration spent on the fixation cross. The direction of saccades is defined by the angular deviation of the saccade from the target center. Origin of this measure with double targets was the midline between the two patterns. In the following, scales refer to deviations in visual angle. Furthermore, separate frequency distributions were calculated from the angular deviation scores for all instruction conditions and all Ss. They were compared with each other by means of a Kolmogorov-Smirnov test and if they did not differ significantly they were pooled.

RESULTS

Figure 4 shows the distributions for single targets. There is no difference in angular deviation for targets of high or low dot density. Both distributions are normal and have a standard deviation of 0.75 deg of visual angle. There is no significant difference between Ss nor between instructions.

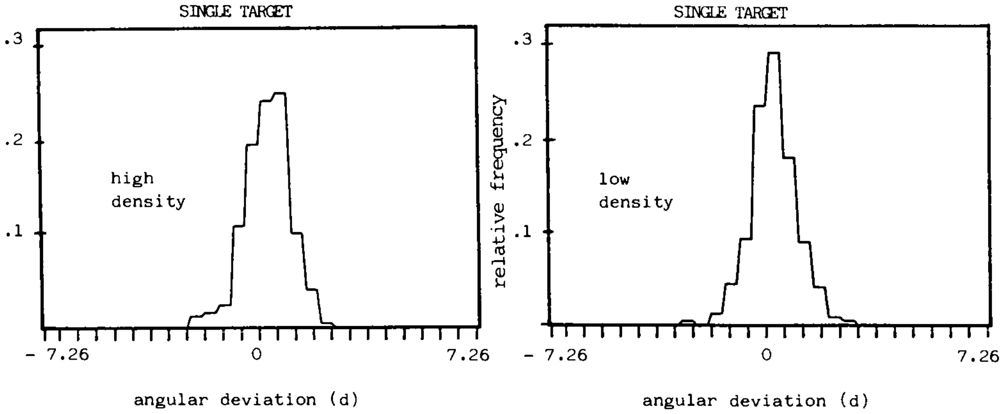

Figure 4: Frequency distributions for single targets with high (left) and low (right) dot density as a function of angular deviation (visual angle).

With embedded targets the results are somewhat similar. Target and distractors differ in dot density. Figure 5 shows the results of the condition with a high density target and low density distractors. The Ss were instructed to find the bright target. The distribution is practically the same as for single targets. And the distribution for a low density target and bright distractors is not very different either (Fig. 5). The instruction here was to find the low density target. This shows that the complexity of the task has no effect on the direction of the first saccade.

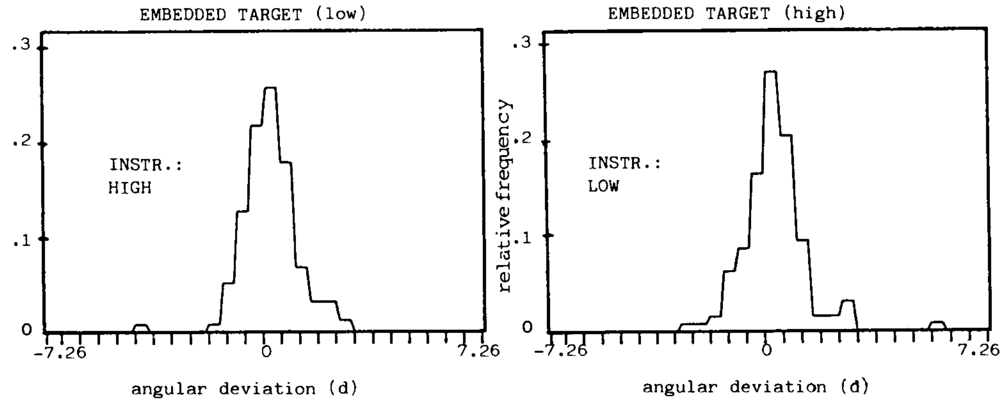

Figure 5: Frequency distributions for embedded targets with low density distractors and the instruction to find the high density target (left) and with high density distractors and the instruction to find the low density target (right) as a function of angular deviation.

However, one could expect that the more difficult task is performed slower. This hypothesis was tested by an inspection of the corresponding saccade latencies. Figure 6 shows the average latencies for single targets and embedded targets. We found indeed an increase in latency if there are distractors. The 95% confidence intervals were less than ∓ 5 msec. So all the results shown are significant.

A more complex picture emerges if the different instructions are taken into account. The inspection of targets could either be free or compatible with the instruction (for example searching for a low density target when a low density target is given) or the inspection could be incompatible with the instruction (i.e. searching for a low density target also there were none or many). Short latencies were found for single targets and compatible inspection. On the other hand, compatible inspection is associated with long latencies if targets were embedded (Fig. 7). This result seems paradoxical. But there is an explanation if one keeps in mind that "compatible" means, the observer had to concentrate on one target out of seven distractors and "incompatible" means that the S could choose any one out of seven targets. Thus, more decisional complexity led to an increase in saccade latency of 85 msec. The fixation accuracy, on the other hand, did not decrease, even under the most complex conditions as re-

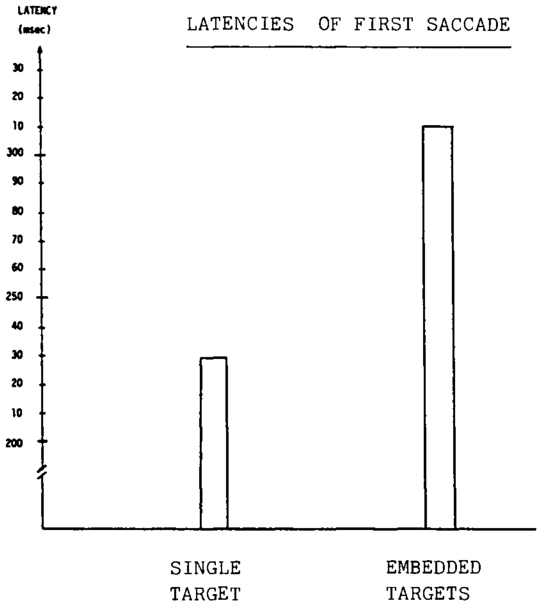

Figure 6: Average latencies as a function of the target type.

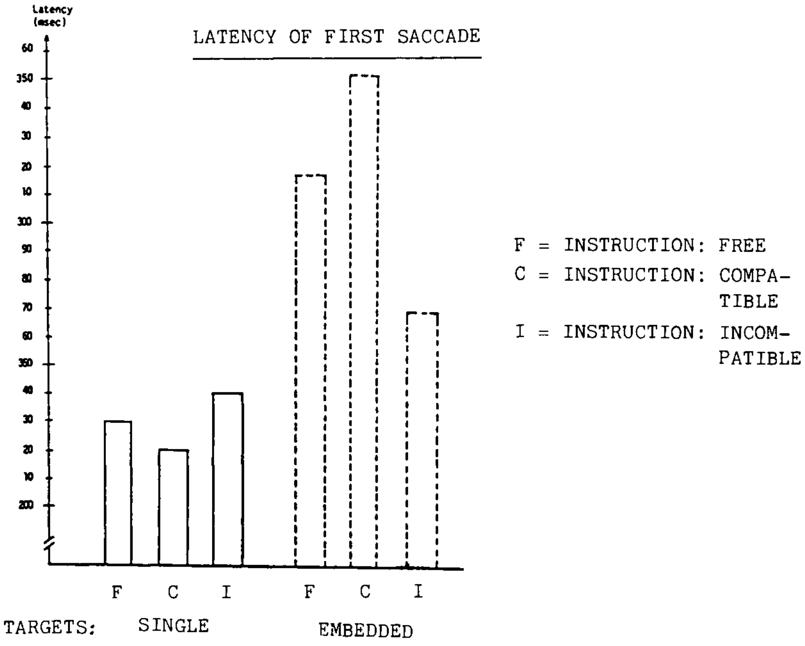

Figure 7: Average latencies as a function of instruction and target type.

ported above.

With the double targets we analysed the following stimulus conditions: the two targets were either close to each other (5.5 of deg visual angle) or far (11 deg), and they had the same density (both low or both high) or different densities (high and low together). At least for "close" and "same" we expected a global effect, that is the saccade falling in between the targets. Figure 8 shows the frequency distribution of the angular deviations with the same targets close to each other. Although it is clearly a bimodal distribution, there are at least some of the saccades that reflect a global response. If the distribution is unfolded according to the three subgroups with the different instructions, we found two different distributions with the instruction to look for bright targets (see Fig. 9). However, under free inspection and with the instruction to look for low density targets three peaks were found in the frequency distribution. This indicates that besides the bistable responses there were also several global responses. Obviously this evidence is rather weak and awaits further support.

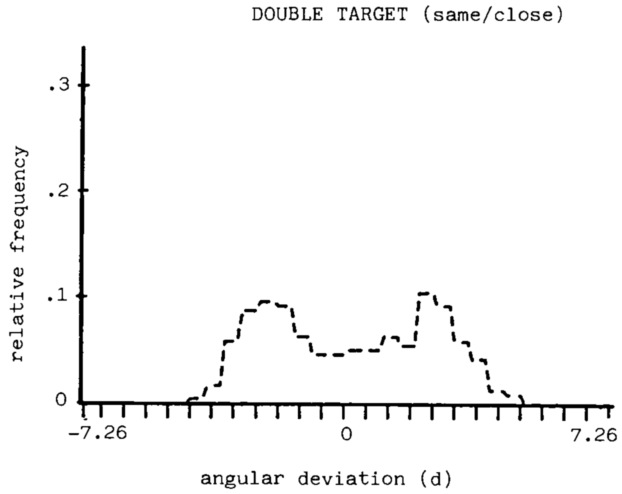

Figure 8: Frequency distribution for double targets that were close together and had the same dot density, as a function of angular deviation.

Under all other double target conditions, bistable responses were found if the two targets were the same. If the instruction constrained the choice, unimodal response was found around the corresponding target.

Figure 10 shows the saccade latencies with double targets. In all three groups latencies were longer if the two targets were of the same density compared

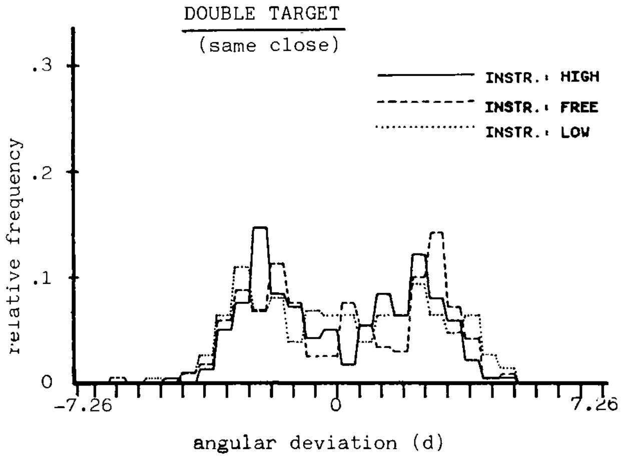

Figure 9: Frequency distribution for double targets (same/close) unfolded according to the instruction conditions (free choice, find the low, the high dot density target) as a function of angular deviation.

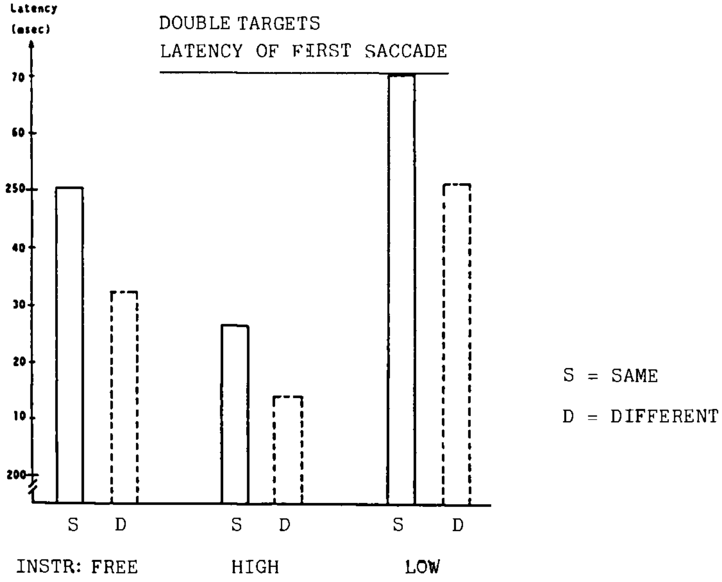

Figure 10: Average latencies for double targets as a function of dot densities and instruction conditions.

to targets with different densities. Furthermore, there is an influence of the instruction: free inspection led to a medium latency, looking for high densities results in fastest performance, and looking for low densities gave the slowest.

CONCLUSION

It is hardly possible to explain the results by a simple automatic response system. It rather must be assumed that there is - dependent on the complexity of stimulation and the task of the observer - a hierarchic response system, relatively fast and almost automatic with simple stimuli, but having additional control processes for more complex situations. The result is a highly adaptive trade-off between speed and accuracy in the saccadic system.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

TWO WAYS OF IMPROVING SACCADE ACCURACY

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Recent studies show that, when a stimulus configuration appears in peripheral vision, the gaze is strongly attracted by its center of gravity. To explain these results, we propose a hypothesis concerning the mechanism responsible for calculating the saccade's spatial characteristics. The general mechanism underlying our hypothesis is based on two main ideas. First, target localization can become more and more precise with time because higher and higher spatial frequencies can be used for processing of sensory information. But secondly, this increasingly detailed information can be extracted only from a more and more limited area. This hypothesis predicts that there should exist two ways of improving saccade accuracy towards a target : increasing saccade latency and increasing target position predictability. These are tested in two experiments, which confirm that gaze attraction to the center of gravity of the configuration can indeed be greatly reduced.

INTRODUCTION

When an isolated stimulus is presented in peripheral vision, the saccadic response is normally accurate, but, if a distracting stimulus is present somewhere near the target, the saccade can become much less accurate. The influence on saccade amplitude of non-target elements present in the visual field has been studied in a variety of conditions (Coren and Hoenig, 1972; Findlay, 1981, 1982, 1983; Deubel, Wolf and Hauske, 1984). All these studies show that saccade amplitude is such that the first fixation is close to the center of gravity of the stimulus configuration. Deubel et al. (1984) proposed a spatio-temporal model to explain these results. But the influence of cognitive factors on saccade amplitude has never, to our knowledge, been studied directly. Yet, as soon as several stimuli are simultaneously presented, it is necessary to extract one target element from these stimuli. It should therefore be interesting to directly study how cognitive factors modulate oculomotor behavior when the subject has to search for this target. We wish to propose here a hypothesis concerning the mechanism responsible for calculating the saccade's spatial characteristics while taking into account the influence of cognitive factors. We shall then present two experiments which test two predictions of our working hypothesis.

HYPOTHESIS ABOUT THE CALCULATION OF THE SPATIAL CHARACTERISTICS OF THE SACCADE

Consider a particular situation. Take for example the case where a string of nine randomly selected letters is presented in peripheral vision (see Figure 1). Within the string, the target letter is marked by a pair of plus signs situated directly above and below it. When the stimulus appears, the Subject is fixating a central fixation mark. His task is to saccade directly to the target letter in order to decide whether it is a vowel or a consonant.

Figure 1

Example of stimulus configuration. The isolated dot represents the central fixation point. The two plus signs indicate the position of the target letter which is in this case the eighth one. The string of nine letters is presented either on the left or on the right of the fixation point at one of two possible eccentricities (the edge of the string nearest the fixation point is at 2.5 or 5 degrees). The width of the letters is 3.2 mm (as is also the blank space between them), subtending an angle of .31 degrees at the eye. The total range of target letter eccentricities is from 3.5 to 10 degrees from the fixation point.

Figure 2 provides a simplified representation of the general mechanism underlying our hypothesis. We shall first examine how sensory information is processed and secondly how the eye's saccade behavior is organized.

We hypothesize that sensory information gives rise to a representation in the brain that may be described in terms of a sensory map. Take the case of a uniformly lit visual field. In such a case, the sensory map is uniformly stimulated. Before the appearance of the stimulus, our attention is evenly distributed over the part of the visual field where the stimulus can appear (the large circle at the top of the Figure represents the size of this region of initial attention while the isolated point indicates the position of the gaze center). When a configuration, identical to that presented in Figure 1, appears in peripheral vision, the stimulation of the sensory map is altered, producing higher levels of activation in the zone corresponding to the configuration. In order to show the effect of the Cortical Magnification Factor (see Rovamo and Virsu, 1979), we have plotted the stimulus in a deformed shape. An analysis in low spatial frequencies is carried out which allows us to determine where in the visual field the stimulus is situated. With time, analysis using higher and higher spatial frequencies is done so that information about target location becomes more and more precise. But we hypothesize, however, that processing of this increasingly precise information to locate the target is possible only from a more and more restricted area. This hypothesis is in fact based on the idea of limited capacity processing of sensory information :

- one can either remain at a low level of analysis (using low spatial frequencies) covering a large area of the visual field (as we can see at the top of Figure 2),
- or one can choose a higher level of analysis (using high spatial frequencies) in order to obtain more precise information, but this information will be processed from only a smaller area (as we can see on the lower part of Figure 2).

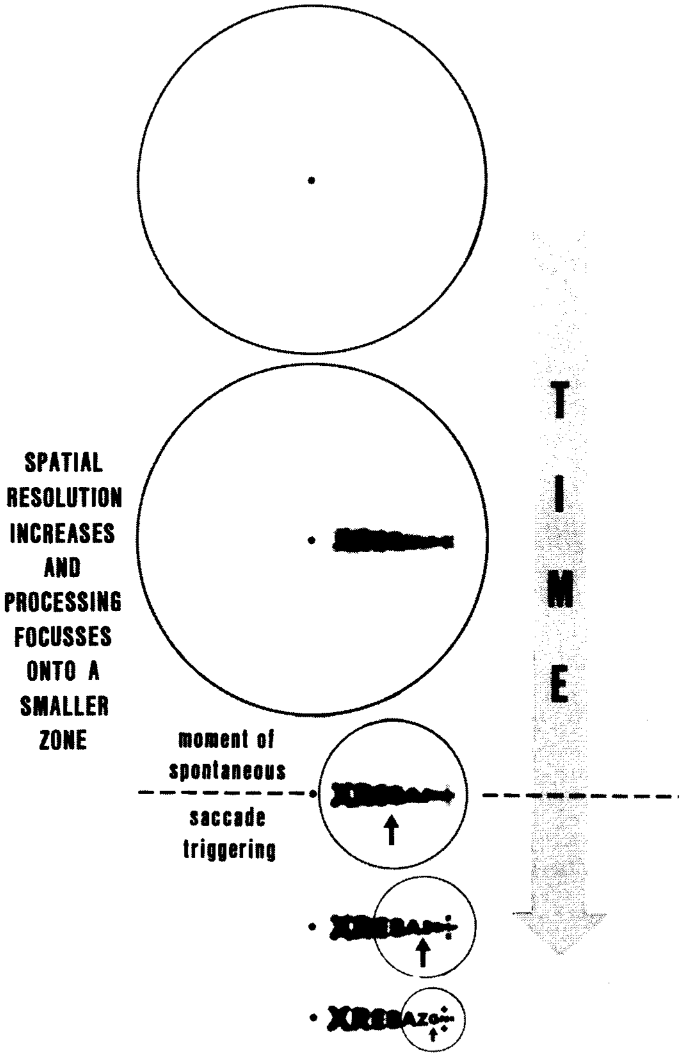

Figure 2

A simplified representation of our hypothesis

Progressively, a more and more detailed processing of sensory information provides more information about the features of the target, allowing it to be located. On the basis of this information, a decisional process determines from which area more detailed information must be collected. At each step of this process, the center of the chosen area is calculated from all the elements present (weighted center of gravity), but also takes into account the most likely position of the target at this moment, as determined by the decisional process. Figure 2 therefore illustrates two principal ideas concerning our hypothesis. First, with time the sensory analysis becomes more and more precise by using higher and higher spatial frequencies (inside the circles, the details become clearer). Secondly, if we want to use the more precise information provided by these increasingly detailed analyses, we have to focus our attention onto a more and more limited area (the size of the circle that represents the region of focused attention diminishes with time).

But all this happens in peripheral vision before the eye has moved. How is the eye's saccadic movement organized ?

At the moment when the decision to move the eyes is taken, the area of focused attention will be centered on a point whose distance from the target depends on the level of visual processing that has been reached. Whatever the time of saccade triggering, the final position of the eye is taken to be close to the center of the area of attention at that time. In Figure 2, means of the different saccade arrival positions related to different moments of saccade triggering are illustrated by arrows. It should be noted that this hypothesis can explain the global effect. What happens in most cases is that the saccade is triggered before a level of processing has been achieved that is high enough to allow accurate aiming of the target. This is illustrated in this Figure by the moment of spontaneous saccade triggering. In this case, the saccade is directed to a position lying close to the center of gravity of the stimulus configuration.

Two direct consequences of this hypothesis are expected :

a/ If the Subject is given beforehand sufficient information concerning the target position so that at the moment of spontaneous saccade triggering he already knows where the target will lie within the stimulus configuration (even though visual processing allowing its localization is not yet completed), then the saccade amplitude should be more accurately adjusted to the target position than if no prior information is given at all. For example, in the situation presented here where a string of letters contains a target letter, if the target is always in the same position within the string on each trial rather than randomly changing position, then we expect to observe an improvement in saccade accuracy. Indeed, in such a case, a gross contour analysis could allow the precise position of the stimulus to be deduced. It is the hypothesis that was tested in Experiment 1.

b/ If saccade triggering is delayed beyond the moment of spontaneous triggering, then localization of the target is improved because more time is available for detailed processing of sensory information, therefore leading once again to an improvement in saccade accuracy. This hypothesis is not new and is compatible with the data obtained by previous research (see for example Findlay, 1981; Viviani and Swensson, 1982; Ottes, van Gisbergen and Eggermont, 1984, 1985) and also in speed-accuracy trade-off studies (see Kapoula, 1984). Unfortunately, in all these studies the observed effects are rather weak due to the narrow range of latencies used. It is therefore interesting to examine this problem using a much wider range of latencies. This is what we did in our second experiment.

In summary, we have proposed two possibilities which, in line with our general hypothesis, should attenuate the global effect and therefore provide an improvement in saccade accuracy :

- one way consists of making the target position within the string highly predictable
- an other way consists of delaying the moment the saccade is triggered.

EXPERIMENT ONE

Method and Procedure

Subjects fixated a central fixation point after having followed with their eyes the movements of a marker appearing at different positions on the screen for calibration purposes. Then a string of nine letters containing one target letter appeared in peripheral vision (see Figure 1). The target was indicated by two plus signs situated above and below it. The Subject had to saccade directly to the target letter and determine wether it was a vowel or a consonant. There were four positions in the string for the target letter (at the 2nd, 4th, 6th or 8th letter from the central fixation point). The letter string could appear either on the right or on the left of the fixation point at one of two possible eccentricities (the edge of the string nearest to the fixation point was at 2.5 or 5 degrees). Two experimental conditions were compared :

- one where the target position within the string varied from trial to trial (mixed condition)
- another where the target position within the string was held constant throughout the series of trials (blocked condition).

On 20% of the trials within each series, target letters were also presented in isolation, in order to check calibration quality. Four Subjects with normal vision participated in this experiment. The method (stimuli, apparatus and procedure) is described in more detail in Coëffé and O'Regan (1986, submitted for publication).

Results and Discussion

Figure 3 shows the means and standard errors of first landing position within the string as a function of the different positions of the target letters. The C curve (filled triangles) presents the blocked condition where the target position was held constant within the string over different trials, whereas the V curve (open circles) presents the mixed condition where the target position within the string varied from trial to trial. In this Figure, the data for the stimulus presentations on both sides and both eccentricities have been grouped. If first fixations were perfectly accurate, they would lie on the dashed diagonal. We can observe that the first fixations are often inaccurate. The idea of a global effect is that the eye is attracted by the center of gravity of the stimulus configuration, so the overshoot observed for the second letter and the undershoot observed for the eighth one are, in a first approximation, compatible with this idea. Let us underline that these results have nothing to do with a "range effect" (Poulton, 1981; Kapoula,1985) since no effect was found on saccade accuracy between the two eccentricities of the string. In fact, these results extend the existence of a global effect already found with simple luminous dots to the internal part of a complex stimulus. This global effect, however, is modulated by the level of predictability of the target position. When this is kept constant within the string (curve C), saccade accuracy increases : the curve is closer to the diagonal.

It should be noted that this effect cannot be explained either by differences in latencies, since they are identical in the two conditions (means are 216 ms for the blocked condition and 214 ms for the mixed condition), nor by more repetitive eye movements being made in the blocked condition compared to the mixed condition, since a great number of different movements were made in tracking the calibration marker appearing at different positions on the screen before each trial.

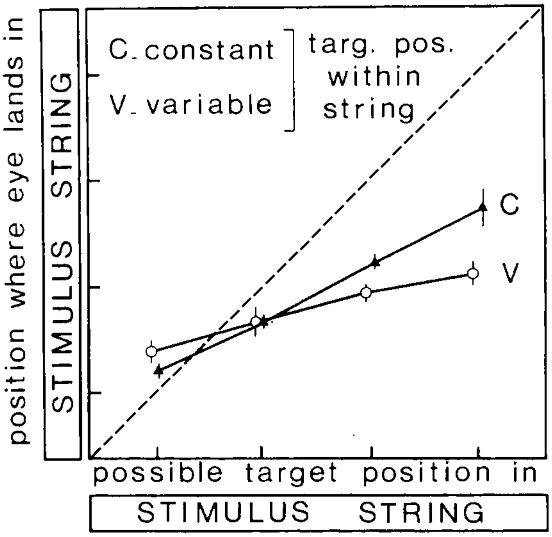

Figure 3

means and standard errors of first landing position within the string of letters as a function of the different positions of the target letters. Open circles correspond to the mixed condition in which the target letter position changes from trial to trial. Filled triangles correspond to the blocked condition in which the target position is kept constant within the string during an entire series of trials. Eccentricities as well as sides of presentation have been meaned in this Figure.

We therefore explain these results (within the framework of our hypothesis presented earlier) by the fact that prior knowledge of the target position within the string allows the Subject to use the contour information of the configuration more effectively. Indeed, using only a contour analysis carried out relatively early, the Subject was able, in the blocked condition, to locate the target with reasonable accuracy and use this information in programming the saccade.

EXPERIMENT TWO

The second way of improving saccade accuracy is, according to our hypothesis, to delay the moment when the saccade is triggered.

Method and Procedure

We wanted to test this hypothesis by controlling saccade latencies so that the Subject had to observe certain imposed minimum latencies. These were controlled by asking the Subject to maintain fixation on the central fixation point until it disappeared. If a saccade was detected by the computer before the fixation point had been removed, an error tone sounded and the trial was interrupted and repeated later in the same series. This type of reinforcement was found to be very effective and we were able to collect a wide range of observed latencies. Four conditions of minimum latency were used (50, 200, 350 and 500ms). Of course, the fact that the minimum latencies were fixed does not necessarily guarantee that the actually observed latencies will increase as a function of these minimum latencies in a uniform manner. Nevertheless, this is roughly what we did observe (means are 208, 327, 559 and 720 ms for the 50, 200, 350 and 500 ms conditions respectively and standard errors are 37, 83, 53 and 124 ms respectively). The stimuli were the same as in Experiment 1, that is nine-letter strings with one target at one of the same four possible positions. The side of stimulus presentation and the target position within the string were determined at random on each trial. The minimum latency conditions, however, were kept constant for each series of trials. As in Experiment 1, the data recording quality was controlled by randomly presenting isolated letter targets within each block of trials and the saccade accuracy was shown to be satisfactory on these trials. The same four Subjects as in Experiment 1 participated in this Experiment.

Results and Discussion

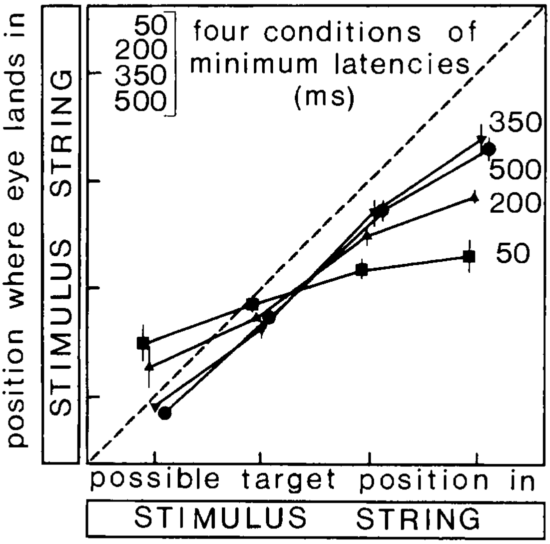

Figure 4

means and standard errors of first landing position within the string of letters as a function of the different positions of the target letter. Each curve corresponds to a specific minimum latency condition so that first landing positions within the string are therefore presented for the four minimum latency conditions. Sides of presentation have been meaned in this Figure.

Figure 4 shows the main results of Experiment 2. We can see that when the minimum latency increases, saccade accuracy improves. In the 50 ms condition, saccade accuracy is very poor. With greater and greater latencies, the curves rotate and approach the diagonal which represents perfect accuracy. In a more detailed discussion of the present work (Coëffé and O'Regan, 1986), these data are further analyzed in terms of the correlation between latency and accuracy. In summary, because, unlike earlier work, we used a wide range of latencies, we were able to demonstrate the effect of latency on saccade accuracy : longer latencies diminish the global effect.

CONCLUSION

The two experiments presented demonstrate that improving saccade accuracy is possible in two ways :

a/ if the Subject knows in advance the target position within the string
b/ if the moment the saccade is triggered is delayed.

These results are compatible with our general hypothesis presented at the beginning of this paper. According to this hypothesis, in order to ignore the non-target elements in the calculation of saccade amplitude, a level of processing that allows the correct localization of the target must have been reached. For this purpose, a decisional process that directs the processing of sensory information towards the area of the visual field containing the target comes into operation, and such a process requires a certain amount of time. But if information concerning the target's location is already available to the Subject, then a high level of sensory information processing is no longer necessary for the appropriate programming of the saccade. A lower level of processing will be sufficient to allow the extraction of information necessary for target location with the same accuracy.

One other aspect of our results appears interesting. How can we explain why the eye didn't wait longer in Experiment 1 before triggering the saccade since this would have allowed an improvement in saccade accuracy ? A more detailed analysis of our data show that the total time necessary for the eye to accurately fixate the target was mostly shorter when it used an intermediate fixation than when it delayed saccade triggering to attain the target directly with a single saccade. Thus it appears that a "time-saving" strategy may well explain the relatively early moment of saccade triggering observed. As a final point, let us point out that the present results show that the global effect, that is the influence of non-target elements on saccade amplitude, can be greatly reduced. This suggests that the eye's attraction to the center of gravity of the configuration is not as systematic as a number of previous studies have implied.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

ADJUSTMENTS OF HAND POINTINGS TO VISUAL TARGETS DO NOT NEED VISUAL REAFFERENCE FROM THE MOVING LIMB

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Evidence is presented to show that the trajectory of a reaching movement toward a visual target in the dark can be modified when displacing the target, in spite of subjects' inability to perceive the change in the location of the target. These findings demonstrate that (1) visual reafference about the relative positions of the hand and the target is not necessary for visually-driven corrections in reaching to occur and (2) the visual mechanisms that maintain the apparent stability of a target in space are dissociable from those that mediate the visuomotor output directed at that target.

INTRODUCTION

When we reach toward an object suddenly appearing in our peripheral visual field, our arm extension toward the object is associated with eyes, head and body orienting in such a way that the object falls on the fovea. The onset of electromyographic activity in the ocular and brachial musculature is usually simultaneous or separated by only a few tens of milliseconds (Biguer, Jeannerod and Prablanc (1982)). Nevertheless, because the eye is influenced much less by inertial and gravitational forces than the limb, the saccadic eye movements directed at the target are typically completed while the hand is still moving. Indeed, the first and largest of the saccades made toward the target is often completed before (or shortly after) the hand has begun to move. This means that during a reaching movement the target will be located on or near the fovea as the hand moves toward it. Theoretically then, information uptake about the position of the target is provided by central vision and can be used to correct the trajectory of the hand as it moves toward the target. The most accepted view of how reaching movements are programmed is the following (Keele (1981); Paillard (1982)): the initial movement of the limb is ballistic and is programmed on the basis of visual information about target position derived from the peripheral retina. As soon as the target is foveated, however, amendments to the motor program (and thus corrections in the trajectory) are made on the basis of the dynamic feedback about the relative positions of the hand and the target as detected on the retina. This feedback depends upon comparing the position of a seen hand with a seen target after the eye has foveated the target.

However, some basic observations about reaching movements cast doubt on the validity of such a view. Subjects who cannot see their hand, for example, are more accurate when the target remains visible than when it disappears after the reach has begun (Prablanc, Echallier, Komilis, Jeannerod (1979); Prablanc, Pélisson, Goodale (1986)). This kind of result suggests that visual feedback about the relative positions of hand and target is not the only source of information allowing the accuracy of reaching movement to improve. Information derived from proprioception or even efference-copy of the motor commands may also play a role in these situations. Unfortunately, little attention has been paid to the way in which such information can influence an ongoing reaching movement. Instead, it seems to have been assumed that any adjustments that are made to the trajectory of a reaching movement are dependent upon seeing the hand moving with respect to the target.

It was for this reason that we decided to examine whether subjects could modify an ongoing reaching movement on the basis of new visual information uptake of target position when vision of the moving hand was not available. If they could, then this would provide evidence that modification of a reaching movement need not rely upon vision of the hand with respect to the intended target. Any adjustments to the trajectory of the moving limb would instead have to depend on information derived from proprioception or efference-copy of the motor commands sent to the limb.

METHOD AND PROCEDURE

In carrying out this work, we took advantage of the fact that during a reaching movement the actual eye movement is much earlier than the hand movement. It was possible therefore to change the position of the target during the point of highest velocity of the first saccade, just as the hand had begun to move. This procedure was applied to create an artificial error around the beginning of the pointing movement without the subject perceiving a change in the location of the target. Since subjects typically undershot targets with their first saccade, they had an opportunity to make a larger or smaller correction saccade and to modify the trajectory of their limb movement to compensate for the change in the position of the target.

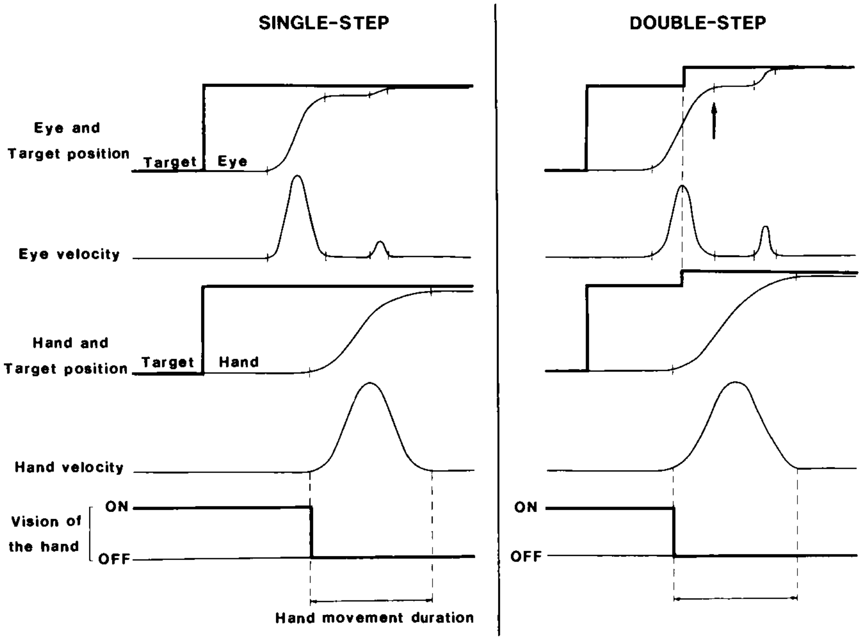

Figure 1
Schematic diagram illustrating the spatiotemporal organization of the movements of eyes and hand in response to single- (left) and double-step (right) displacements of the target. As the diagram indicates, vision of the hand was prevented at the onset of hand movement in all trials. The second target displacement on double-step trials (restricted to 10% of the initial displacement) occurred just around the point of peak velocity of the first saccade, that is after the onset of hand movement. Subjects were thus not aware of the existence of double-step trials, and both kinds of trials were randomly mixed during the same experimental session (single-step targets to 30, 40 and 50cm; double-step targets to 30-32cm, 40-44cm and 50-54cm). The arrow indicates the point at which visual information about new target position can be processed.

The experiment was carried out in the following way. Four naive subjects were seated in turn in a darkened room with the index finger of their right hand resting on a small visual target located in a central position on a platform directly in front of them. Each was instructed to move his finger as quickly and as accurately as he could to the new location of the target as it stepped from its central position to a more peripheral one. At the beginning of a trial, the subject viewed his hand and arm through a large half-reflecting mirror. The target consisted of a small LED positioned above the mirror in such a way that its virtual image appeared below the mirror on the same surface as the subject's hand. The subject's head was fixed with a bite bar, and horizontal eye movements were monitored by dc electro-oculography. The position of the subject's index finger at the beginning and end of a pointing movement was derived from resistive paper that covered the surface on which the virtual image of the target was located. The trajectory was reconstructed from a photograph of a flashing infrared LED (2 ms at 100 Hz) attached to the end of the subject's finger.

As soon as the subject's index finger left the surface on which the central target had been located, the subject's view of his hand and arm disappeared. It reappeared only after the target moved back to the central position, and when the hand began to move back in preparation for a new trial. This meant that as soon as the subject moved his limb toward the peripheral target he had no visual feedback about his pointing movement. On half the trials (single step), the target stepped from its central position to a randomly determined position 30, 40 or 50 cm to the right and stayed there until the subject's finger re-contacted the surface. On the remainder of the trials (double step), the target jumped to one of these positions, followed by a second jump to a new position 10% further away from the center. The second step occurred just after the first saccade reached its peak velocity. The two conditions are illustrated schematically in fig. 1. Thirty single- and 30 double-step trials were presented to each of the four subjects in random order. Subjects were not told that the target would sometimes change position during the first eye movement. Randomization of the single- and double-step trials was critical to the experimental procedure. Changing the retinal feedback from a saccade (in a systematic way) is known to result in a progressive and adaptive change in the gain of the saccades (McLaughlin (1967); Henson (1978)). By presenting the subjects with single- or double-step targets in random order, we were able to keep the gain of the oculomotor response constant and could discard the adaptive process that occurs with modified feedback. Moreover, would the subjects have been able somehow to detect the second jump, they would have been unable to predict when such a trial would occur. The entire experiment was controlled and monitored by an on-line computer.

RESULTS

At the end of the experiment each subject was asked what he thought had happened and whether any of the targets had changed position during the pointing movement : none could report double-steps. The quantitative results of this experiment were clear and unambiguous. As Fig. 2a illustrates, although the subjects consistently undershot the position of the target, the distributions of their final positions in the single- and double-step conditions were separated by a distance nearly equal to the size of the second displacement of the target (an analysis of variance yielded no significant differences between undershoot errors at any of the 3 pairs of amplitudes). In other words, the subjects were correcting the trajectory of their limb movement to fully accomodate this displacement. Moreover, the duration of a limb movement made to a double-step target corresponded to the duration of movement that would have been made to a single-step target located at the same final position (Fig. 2b). Thus, no additional processing time was required during the double-step trials. Following these clear results, planar finger trajectory was recorded from other subjects during the same pointing task. To compare kinematics of pointings at a given target location between single-step and double-step trials, trajectories were recorded for a 44cm single-step target and for a 40 to 44cm double-step target. The horizontal velocity and acceleration profiles (Fig. 3) were very similar in both conditions; the differences in finger deceleration between single- and double-step responses being not statistically significant. In particular, velocity profiles of finger trajectory to a double-step target showed no "inflexion point" to indicate a reprogramming of the manual response.

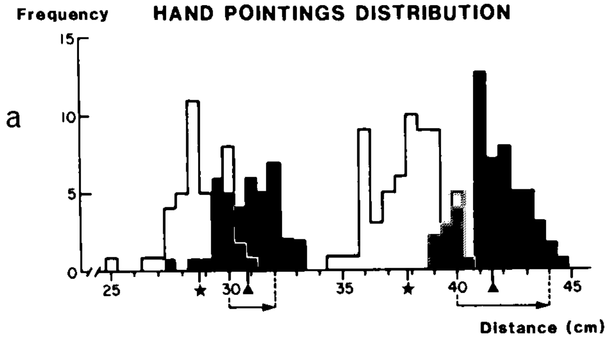

Figure 2a

Frequency distributions of the final positions of the index finger on single- (white histograms) and double-step (black histograms) trials for the 30 and 32cm and the 40 and 44cm targets. The size of the second target displacement is indicated by the small arrows on the abscissa. For a single-step to 30cm, the distribution of pointings represented by the white histogram is undershooting as shown by the mean response (star). In trials on which this target was further displaced during the saccade from 30 to 32cm, mean response (triangle) indicates also an undershooting; but the distance between the two histograms is equal to the target shift. Same phenomenon applies for target shifts from 40 to 44cm and from 50 to 54cm (not shown because of insufficient data).

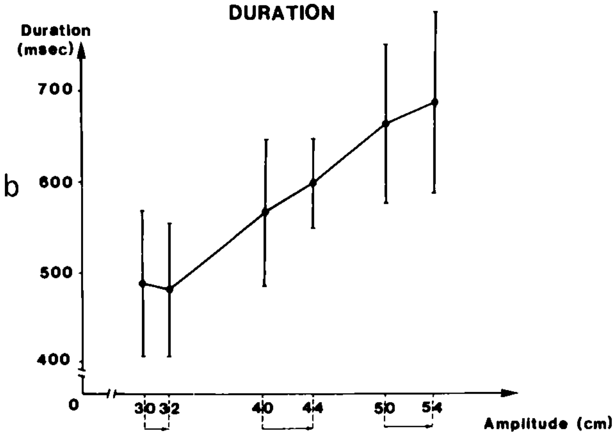

Figure 2b

Mean duration of the hand movements plotted as a function of amplitude of the target final position . Vertical lines indicate standard deviations. Note that pointings on double-step trials belong to the same duration-amplitude relationship as pointings on single-step trials. Thus no additional reaction time appears within the total duration of responses to double-step targets and no increase in variability of movement duration can be observed.

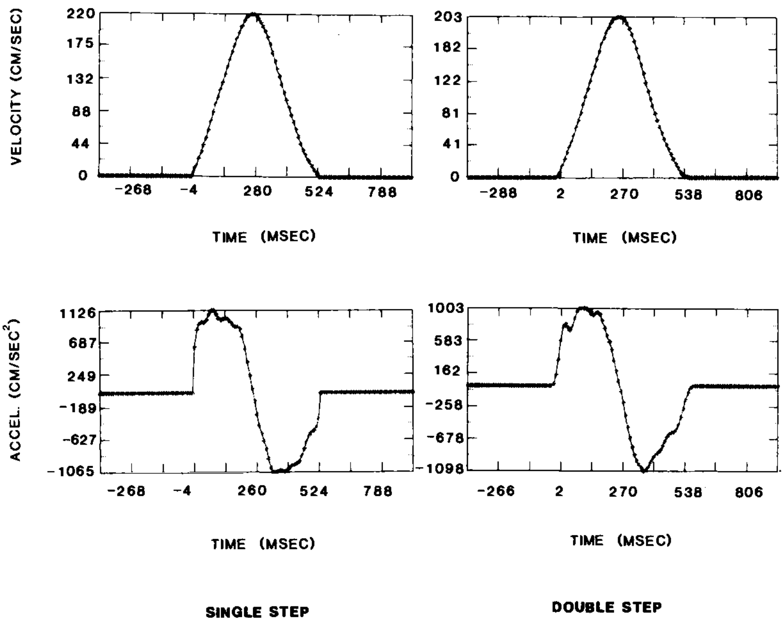

Figure 3

Time-course of kinematic parameters of horizontal hand trajectory for a 44cm single-step target (left) and for a 40 to 44cm double-step target (right). Velocity and acceleration profiles were computed using a polynomial approximation method with a 12Hz cut off frequency; they were then averaged for each subject and each condition (for that subject, 9 and 8 repetitions were averaged for single- and double-step, respectively). Due to the averaging method, the duration of the movement read from the time axis (time 0 = onset of movement) corresponds to the maximum duration for the subject and the condition concerned. Note the absence of an "inflexion point" on the velocity profiles in both conditions. Simular results could be observed on individual hand trajectories.

DISCUSSION

These results depart from previous studies on double-step stimuli where it has been shown that either oculomotor responses (Täumer (1975); Becker and Jürgens (1979)) or limb responses (Megaw (1974); Georgopoulos, Kalaska and Massey (1981); Soechting and Lacquaniti (1983)) to a double-step stimulus could overlap. Even when midflight modification of saccade trajectories can be induced by double-step stimuli under particular conditions (Van Gisbergen, Van Opstal and Roebroek (this volume)), such oculomotor responses did not look like saccades at single-step targets. Indeed, except for the delayed responses reaching directly the second location of the target, their trajectory always showed a clear "inflexion point" whose latency with respect to the second step increased significantly the total duration of the response. In such instances, the visuomotor system in the best cases could work with a constant delay. Thus classical double-step experiments dealt more with the reprogramming capabilities of the sensorimotor systems, while ours was more directed toward understanding how retinal feedback from the saccade allows an uptake of stimulus location and thus can influence the ongoing limb motor output.

The present results strongly suggest that when rapid eye and hand movements are directed at a visual target, an initial set of signals is sent to the muscles controlling both the eye and the hand based on information about the position of the target that is available on the peripheral retina. After the first saccade, however, the combined input from retinal and extraretinal signals updates the information about target position (Prablanc, Pélisson and Goodale (1986)), which is then immediately used for "fine-tuning" of hand trajectory. If this hypothesis is correct, then it becomes much clearer why the duration of a movement is the same for a given position of the target, independent of whether that position was achieved by a single or a double displacement of the target. In either case, the same post-saccadic information would be used to update the motor signals controlling the hand trajectory (at least if the amplitude of the second displacement in the double-step condition is less than 10% of the initial displacement). In other words, the apparent correction in the trajectory that occurred on double-step trials could be nothing more than the normal updating of the motor programming that occurs at the end of the first saccade on an ordinary trial.

All these modifications in the trajectory of the pointing movement were made without the aid of any visual feedback about the limb position. Thus, the new information about the location of the target in visual space that was obtained at the end of the first saccade must have been combined with information about the current trajectory of the hand that was derived from non-visual sources. However, our experiment said nothing about the nature of this non-visual information that was used. Two possible candidates are proprioceptive feedback from the hand and limb and/or efference-copy of the signals sent to hand and limb. Either or both of these sources of information about the position of the limb could have been compared to the central spatial representation of the target provided by retinal and extra-retinal signals at the end of the first saccade. Whatever the mechanisms might be, our experiment has shown that a fast and efficient loop can modulate the limb motor output in the absence of visual hand reafference.

At no time in this experiment did any of the subjects realize that the target had stepped to a new location while they were reaching toward it. Nor did the subjects report any peculiar sensation about their reaches on double-step as opposed to single-step trials. In short, they failed to perceive the change in target position even though the reaches were modified to accomodate that change. Indeed, had the subjects perceived the change in target position that occurred on double-step trials and, on the basis of this perception, quite consciously altered the trajectory of their reach, then the duration of the movements on these trials would have fallen well outside the amplitude-duration curve obtained on single-step trials and would have given the same results as with classical double-step experiments. The fact that this did not occur (see Fig. 2b) is additional evidence that subjects were treating single- and double-step trials in the same way and, as we have already argued, suggests that the type of "correction" on double-step trials was not different from the normal fine-tuning of the trajectory that occurs at the end of the first saccade on single-step trials. A similar dissociation between eye-hand motor output and perceptual report has been observed in experiments in which subjects have been asked to point toward or report verbally about the position of a visual target that may or may not have moved (Lennie and Sidwell (1978); Bridgeman, Lewis, Heit and Nagle (1979)). The failure to perceive the displacement in the present experiment may reflect the broad tuning of perceptual constancy mechanisms that preserve the identity of a target as its position is shifted on the retina during an eye movement. The results of our experiment would suggest that artifically induced displacements in real space of less than 10% of the initial displacement will not disrupt this constancy provided the actual displacement in target position occurs during a saccade. Mechanisms that construct the percept of the target are clearly dissociable from those that mediate visuomotor control of arm movement directed at that target. This dissociation, which we obtained in normal human subjects, is reminiscent of the behaviour of cortically blind patients who fail to perceive visual targets even though they can point toward them (Weiskrantz, Warrington, Sanders and Marshall (1974); Perenin and Jeannerod, 1978)).

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VISUAL STABILITY AND DIRECTION OF RETINAL IMAGE DISPLACEMENT DURING EYE MOVEMENT

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By means of an optical system of two Dove prisms fixed onto the subject's eyeball the angle of incongruity (γ) between the eye movement direction and the retinal image displacement was modified ($0^\circ \leq |\gamma| \leq 180^\circ$). The method showed that 1) there exist unusual kinds of eye movements closely connected with γ, 2) the visual instability occurs only if $|\gamma| \leq 90^\circ$, 3) the apparent velocity of objects and smooth eye movement velocity are equal. New interpretation of visual instability effects is proposed.

INTRODUCTION

Under natural conditions of perception each eye movement is accompanied by equal displacement of the retinal image. Thus, for example, if eyes turn 10° to the right, the retinal image also moves to the right by 10°. The congruity between eye movement and retinal image movement has long been considered by researchers in two connections. First, the displacement of a retinal image caused by goal-directed eye movement does not result in the perception of moving environment or of objects changing their location. Second, the displacement of retinal images constitutes visual feedback in the eye movement control system. The former relates to the problem of stability of the perceived environment (Festinger and Canon (1965), Skanevski (1976), Whipple and Wallach (1978)). The latter relates to the problem of mechanisms of eye movement regulation (Fender and Nye (1961), Vossius (1972), Robinson (1975)). I am going to discuss experimental data obtained in situations with distorted natural congruity between eye movements and retinal image displacement. The analysis casts new light on both problems, and reveals several new aspects of functioning of the eye-movement control system and of visual perception. I shall limit myself to consideration of discrepancy between the directions of eye movements and displacement of retinal image and to discussion of perceptual stability.

METHOD

The general idea of the research method consists in artificial changes of the optical properties of human eye. A miniature optical system comprising two Dove prisms that sequentially refract light reflected by objects is attached to the eyeball by a special suction cup (Fig. 1). Changing the setting of the prisms, the experimenter may obtain any desired orientation of retinal image in relation to the objects of the environment. Since this orientation remains constant during eye movements, the procedure causes a corresponding incongruity between the direction of eye turn and displacement direction of the retinal image. For example, an artificial turn of retinal image by 45° angle causes a 45° angle of incongruity. In place of the words "the angle of incongruity between the eye movement direction and the retinal image displacement" I shall use the working term "the angle of incongruity" as a synonym denoted with the Greek letter γ.

In more detail the method is described in Barabanschikov, Belopolsky and Vergiles (1982).

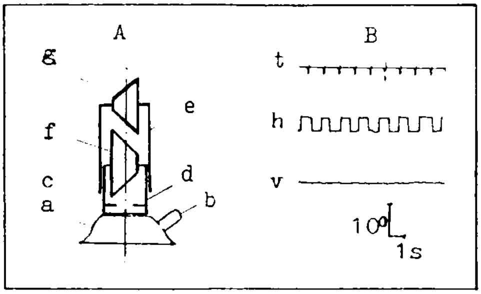

Figure 1
A - Diagram of cup equipped with an optical system enabling the orientation of the retinal coordinates to be varied. a - body of the cup; b - nipple to pump out air; c - diaphragm; d - first tube; e - first prism; f - second tube; g - second prism. B - Eye movements in sequential fixation of two spots ($\gamma = 0^{0}$).

The general experimental procedure is the following. Under the conditions of monocular observation a subject is exposed to immobile spots or scenes. Ss are instructed to fix the gaze on a certain point or a detail of a scene, move the gaze form one point to another, describe the content of a scene or find a certain object. The time of problem solving is not limited. The independent variable, direction of the retinal image displacement caused by eye movements, is varied within the range between 0 and +-180^{0}. Eye movements are registered electromagnetically (Barabanschikov, Belopolsky and Vergiles 1982). Reports of Ss about peculiarities of visual scenes are also recorded.

RESULTS

I shall consider the results in the order of increasing angle of incongruity (γ) and point out five crucial values: 0^{0}; +-45^{0}; +-90^{0}; +-135^{0}; +-180^{0}.

$\gamma = 0$. This is the condition of normal perception. The shift of gaze from one object to another is characterized by a rather precise jump towards the target and stable fixation. The drift speed seldom reaches 1^{0}/sec and its amplitude does not exceed 1^{0}. Perception of objects is stable. No difficulties in analyzing pictures. Records of eye movements show a characteristic chain of saccades, interrupted by a low amplitude drift.

$|\gamma| = 45^{0}$. (Fig. 2). The shift of gaze from one dot to another is accompanied by a series of 3-4 diversely oriented saccades. Eye-turn trajectory has the shape of an arc. The drift component reaches the speed of 4-6^{0}/sec, its amplitude does not exceed 3-5^{0}. Subjectively turning the eye toward the spot does not give rise to difficulties. The subjects report fixation at the same speed as in normal conditions. Objectively, the duration of fixational turn composing saccade chain and drift, grows by 3 to 4 times. Perception of objects remains stable. Picture analysis gives rise to no difficulties. The general view of eye movenents is close to normal.

$|\gamma| = 90^{0}$. (Fig. 3). The shift of gaze from one spot to another at a distance of 5^{0} is accompanied by a series of saccades interrupted by a quick drift. The number of saccades in a fixational turn may attain 40, their amplitudes vary greatly, reaching in certain cases 17-19^{0}. Maximum speed of smooth component of

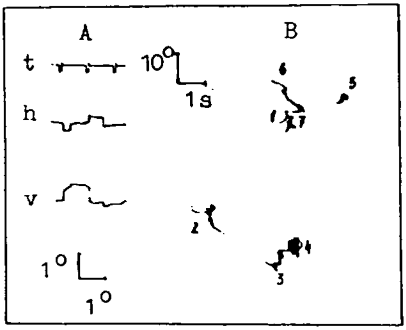

Figure 2
Eye movements in sequential fixation of upper and low spots ($\gamma = 45^\circ$). A - development in time; B - development in space; 1-2-3-4 - trajectory of eye turn from upper to lower fixation point; 4-5-6-7 - trajectory of eye turn from lower to upper point.

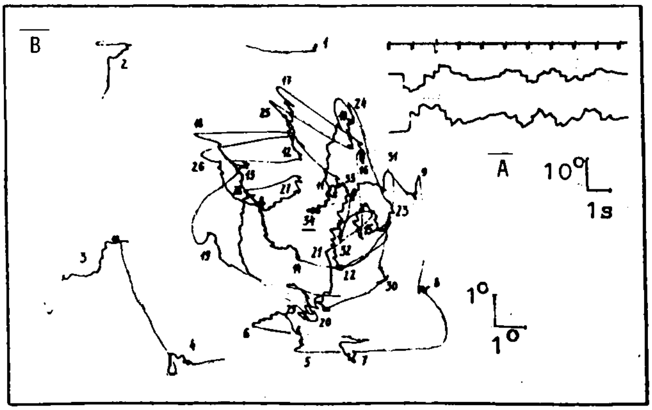

Figure 3
Eye movement recording in transition of the gaze from upper to lower fixation point ($\gamma = 90^\circ$). A - development in time: B - development in space. Numbers mark the sequence of movements.

the movements is 10-12°/sec. Quick drift and jumps in the opposite direction resemble nystagmoid oscillations of an eye. The eye-turn trajectory is reminiscent of a spiral turning over the fixation point. In certain cases 2-3 seconds before fixational pause, low amplitude (up to 4-6°) smooth rotation movements occur. Duration of fixational turn and its spatial characteristics depend on the subject's training. It has been observed that continuous fixation of gaze on the object is a pre-condition for the optimal eye-turn (which takes minimum time). Unlike under $\gamma = 45^\circ$, the unusual nature of the fixational turn is experienced by the subjects. They point out: (1) the strong impression of "viscosity" during the turning movement, (2) gradual growth of clearness of perception of the objects, (3) perception of smooth low-amplitude movements of still objects in the field of vision during quick drift. The latter fact evidences the disruption of visual stability. Still picture analysing performance does not produce difficulties. Several seconds suffice for them to give accurate descriptions. Compared to normal, the general shape of the eye movement activity changes considerably with predominance of the quick drift and emergence of nystagmoid phenomena.

$|\gamma|=135^{\circ}$. (Fig. 4). Two forms of activity predominate in eye movement records nystagmoid eye movements with a frequency of 0,5-3 Hz, and cycles of smooth sinusoidal oscillations with an amplitude of up to 20-25° and speed up to 40-45°/sec. Nystagmoid eye movements emerge during concentration of gaze on the object of fixation. The attempt to "catch" an object as a whole, by a broad attentional field as well as tracking leads to highamplitude smooth oscillations. After a number of continuous attempts one subject out of three managed to fixate the eye on the object. Practically the eye movement task becomes insoluble. Objects in the field of vision seem to move continuously; their speed grows in proportion to the speed of eye movements. Visual problem solving and gaze control produce difficulties.

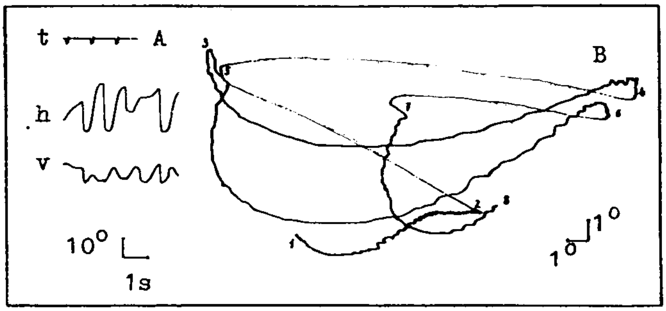

Figure 4
Eye movements in distributed attention over the objects in the field of vision ($\gamma=135^{\circ}$). A - development in time; B - development in space.

$|\gamma|=180^{\circ}$. Two forms of activity dominate in records : There is (1) nystagmus with the frequency of 0,5-4 Hz, amplitude of 5-30° (Fig. 5) and (2) smooth oscillation (rotation movements) with frequency 0,5-0,8 Hz, horizontal amplitude 20-50°, vertical amplitude 10-30° (Fig. 6). Nystagmoid movements are connected with an attempt to fix details of the object; the zone of nystagmoid movements seems to scan the field of vision. Smooth oscillations are caused by attending to an object of large (more than 10°) angular dimensions or when tracking it . The spatial trajectory of these movements forms an ellipse changing dimensions and orientation in space. Visual problem solving is highly impeded. Any immobile object in the visual field is perceived as moving. Under these conditions the type of apparent motion is predicted by the type of eye movements. For example, if the eyes swing in a rotation-like fashion, the objects within the field of vision are perceived as rotating.

So, the growth of incongruity between the direction of eye movements and the corresponding displacement of retinal images gives rise to systematic changes in eye movement activity and visual perception. The span of fixational movements grows, the speed and amplitude of the smooth component grows by one hundred, and specific forms of eye movement activity occur. The perceived environment loses its customary stability and starts to move when the eye turns.

The voluntary control of the gaze is distorted. The strategy of visual problem solving changes.

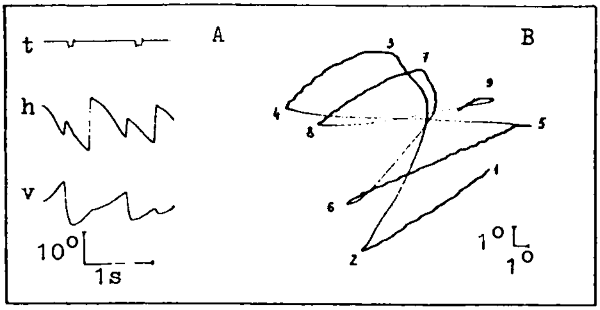

Figure 5
Eye movements in an attempt to fix an object ($\gamma = 180^\circ$). A - development in time; B - development in space. Numbers mark the sequence of eye movements.

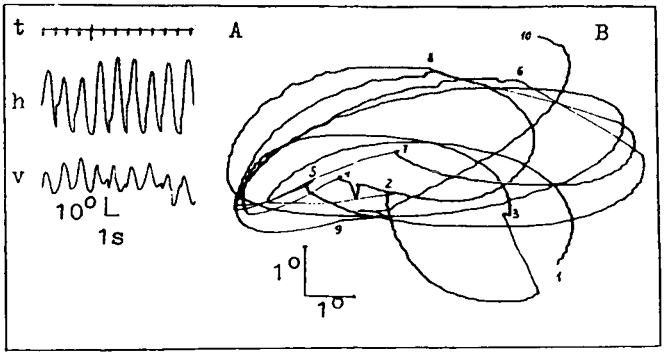

Figure 6
Eye movements in distributed attention over the elements of the viewed picture ($\gamma = 180^\circ$). A - development in time; B - development in space. Numbers mark the sequence of eye movements.

DISCUSSION

Considering these data from the point of view of the problem of visual stability, one may emphasize the following.

(1) Disruption of visual stability occurs only if the angle of incongruity equals or exceeds 90° ($|\gamma| \geq 90^\circ$). Within rather a wide range ($-90^\circ \geq \gamma \geq +90^\circ$) the visual system is insensitive to noncorrespondence between eye movement and retinal image movement. This shows that visual stability has a zone nature. According to our data the range of stability is limited by $|\gamma| = 60^\circ - 75^\circ$.

(2) Within first seconds of wearing the distorting optical device, the character

of eye movement activity starts to coincide less strictly to the projection relations of objects on the retina. It is exactly through of this lack of coincidence that there arises an opportunity to perform the visual and motional task. For example, the gaze may be fixed on an object at $\gamma=135^0$, although theoretically (according to the projection relations on the retina) it is impossible already at $\gamma=90^0$. Consequently, the eye-movement control system this way or other "takes into account" the unusual displacement of the retinal image and adapts itself to new conditions of regulation. However, the adaptive possibilities of the eye movement control system under the conditions of the short-term (30-40 minutes) experiment are rather limited; at $|\gamma|>135^0$ the eye movement tasks can not be fulfilled. The eye movement system's ability to quickly restructure visual-motor relations is evidently closely connected with the zone nature of visual stability, and each one is a pre-requisite of the other.

(3) Beyond the limits of the stability range ($|\gamma| \geqslant 90^0$), changes in parameters (speed, amplitude, form) of the perceived movement corresponds to the changes in parameters of the eye movements. To find the cause of this correspondence I shall consider a simple experiment. A subject is placed before a big mirror at a distance of 25-30 cm. Observation is binocular, with one eye carrying a suction cup with prism, the other not. Because of aniseiconia and binocular rivalry the S can observe in the mirror both movements of the suction cup and reflection of his own face turned at the angle of incongruity ($|\gamma| \geqslant 90^0$). This provides the conditions for direct visual comparison of angular amplitude, frequency, direction and trajectory of specific eye movements with the parameters of the apparent movement of the object (the reflection of the Ss face in the mirror). The result of the experiment is unambiguous. In all the tests Ss perceive simultaneous oscillations of eyes and object. The direction of apparent movement always coincides with the direction of retinal image displacement (γ). Consequently, the only source of perception of movement and change of location under these conditions is the unusual displacement of retinal image caused by the turn of eyes.

I should like to note, that the conditions of the above experiments in certain important respects ($\gamma=180^0$) reproduce the conditions of the experiments by von Holst (Holst (1954)) and Sperry (Sperry (1950)), conducted on insects, fish and amphibia. Up till now these experimental data have provided a background for illuminating analogies between animal behavior and functioning of human visual system. In particular, they have been used as a basis for formulating the well-known theory of "efference copy" ("corollary discharge"). According to this theory, the phenomenon of visual stability is a consequence of mutual substraction of eye movement information received from two different sources, the retina (the displacement of retinal image) and the eye movement centers (the intended eye movement).

In starting the experiments I wished to verify this theory, and should I succeed to use the conceptual framework of the theory to describe the experimental data. However, the outcome of the study suggests the need for an alternative theory. Without going into detail of the procedure of comparison of our results and those by von Holst and Sperry I can just say that the general outcome of such checking was negative. The "efference copy" theory does not account for the zone nature of stability, adaptivity of the eye movement control system, and close correspondence of apparent movement and retinal image displacement beyond the stability range. That is why this theory appeared to be inefficient for the interpretation of our data. Other existing theories of visual stability (Wallach and Lewis (1965), Matin (1972), Epstein (1973), Mac Kay and Mittelstaedt (1974) are also not adequate.

The experimental data observed can be interpreted more adequately in line with the concept of stability being a necessary condition of individual orientation in the environment and being a perceptual norm emerging in the process of philo- and ontogenesis. Stability does not form anew during each visual act but is its pre-requisite and is reconfirmed by each visual act. That is why the first problem of experimental research does not consist in finding out how visual stability is possible, but why it sometimes is disrupted. A key to solve the problem may be found by means of analysis of eye movement functions in visual perception.

Under normal conditions the main function of eye movements is to provide favourable conditions for visual perception, namely fovealization of the object of interest, that is, formation of its clear image in the central part of the retina. Practically any goal-directed eye movement exercises the function of improving object fovealization. Under abnormal relations between direction of eye movement and retinal image the situation changes dramatically. Eye movements acquire simultaneously two opposite functions, fovealization and defovealization. On the one hand they tend to fix the gaze on the object, placing its image into fovea. On the other hand each eye movement (both smooth and saccadic) causes divergence of the image from the fovea. Under these conditions, eye movements play a role of perturbation factor, and the more the direction of retinal image displacement deviates from the norm, the higher effect of the factor. The relation of the positive (fovealization) and the negative (defovealization) effects of eye movements determines whether the environment is perceived as stable or moving. According to our data the perception is stable when fovealization prevails over defovealization ($\gamma > 60^{o}$), i.e. when each eye movement toward the goal brings, at least slightly the image of the object closer to the fovea. In the opposite case the unusual displacement of the retinal image becomes a source of apparent movement. This phenomenon seems to be similar to the perception of movement of immobile objects when one taps slightly with a finger on an eye-ball. However the role of the outer cause is played by the movements of the organ of vision.

CONCLUSION

In conclusion I would like to emphasize that "splitting" natural functions of eye movements and bringing fovealization and defovealization into opposition, one can postulate a mechanism that disrupts visual stability rather than one which maintains it. One can suggest that this mechanism is engaged more often than may seem at first glance. At least it may be discovered when the parameters of eye movements and apparent movements of objects coincide, e.g. the cases of after-image and post-rotation nystagmus. However, verification of this hypothesis requires further investigation.

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SACCADIC EYE MOVEMENTS TO PREDICTABLE VISUAL AND AUDITORY TARGETS (*)

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Predictability is a well known aspect of sensorimotor control in man. When a tracking task is assigned to the subjects and the movement of the target is periodic, the subject's response greatly improves. In the present study saccadic eye movements to predictable auditory targets have been considered. The effects of stimulus predictability have been quantified in terms of saccade latency and accuracy. The results have been compared with those obtained in the same subjects by using periodic visual patterns of stimulation.

INTRODUCTION

When a visual target is made to appear in the visual field of a subject, a saccadic eye movement orienting the subject's gaze towards the target can be elicited. The eye movement starts after about 250 msec from target appearance, and the final eye position can be reached in either one step (single saccade response) or in two or more steps (multiple saccade response) [Young (1962); Robinson (1964)].

Fixation saccades can also be evoked by asking the subject to orient his gaze towards a source of sound (auditory target) that starts operating in the dark. Nevertheless, a number of significant differences have been shown to exist between the characteristics of saccades to visual and auditory targets [Zahn, Abel and Dell'Osso (1978); Zambarbieri, Schmid, Magenes and Prablanc (1982)]. The major differences were concerned with saccade latency and the percentage of multiple saccade responses in relation to target eccentricity.

If a visual target is made to jump between two fixed positions in a repetitive way and the subject is asked to follow the target with his eyes, the latency of tracking saccades decreases progressively to reach a steady state value in about five cycles. Depending on the frequency of target motion, this value may correspond to a delay of less than 250 msec or even to anticipation [Stark, Vossius and Young (1962); Dallos and Jones (1963); Ron (1982)]. In the latter case, eye movement precedes target movement.

No data have so far been made available on learning and prediction in the tracking of auditory targets. On account of the differences observed in saccades to unpredictable targets when

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either visual or auditory targets were used, it was therefore interesting to investigate the buildup of learning and prediction in subjects tracking auditory targets. The aim of this paper is to report the results of a study in which subjects were presented with symmetrical square wave patterns of target motion, the target being either visual or auditory.

METHODS

Five normal subjects with no previous experience of tracking repetitive patterns were examined. Subjects were seated in total darkness. Head movements were eliminated by the use of a dental bite board. Visual and auditory targets were placed in front of the subject at a distance of 80 cm. Visual targets were light emitting diodes and auditory targets were small loudspeakers fed with a square wave signal at 15 Hz.

Each subject was tested in ten separate sessions. During each session subjects had to track with their eyes a target jumping in a periodic way between two fixed positions (10 degrees right and left) . No specific recommendation was given to subjects about tracking accuracy. After 20 cycles of target oscillation, the target was switched off and subjects were asked to go on with their eye movement for at least 5 further cycles as if the target were still present and moving the same way. Five frequencies were considered for both visual and auditory stimulations (0.2, 0.3, 0.5, 0.7 and 0.9 Hz).

All the experiments were carried on under the control of an APPLE II personal computer. Eye movement was recorded by EOG, low-pass filtered at 125 Hz and then analyzed by using an interactive program [Cabiati, Pastormerlo, Schmid and Zambarbieri (1983)]. The parameters considered in this study were the latency and the amplitude of the saccadic response to each target jump. Responses were considered to be single or multiple saccade responses depending on whether a corrective saccade took place within 200 msec from the end of the primary saccade. In the case of multiple saccade responses, the response amplitude was computed as the total eye displacement (amplitude of the primary saccade plus the amplitude of corrective saccades). Responses were considered to be anticipatory when their latency was negative.

For the sake of brevity, the responses following the presentation of visual and auditory targets will be referred to hereafter as "visual" and "auditory responses", respectively.

RESULTS

For both visual and auditory tracking the first saccade in each experimental session followed the first jump of the target with a latency greater than that observed on the average for saccades to unpredictable targets of the same type. The latency of the second response fell in the range of latencies reported for saccades to unpredictable targets. In the next 4 to 6 cycles of target motion the latency decreased further and then started oscillating with an almost constant mean value (Fig. 1). This value was assumed to represent the average steady state response latency in the conditions considered in these experiments.

When the target was switched off, subjects were still able to reproduce with their eyes the previous pattern of the target. The latency of each saccade in this condition was computed with respect to target movement as if it were still going on. After target disappearance the latency could either increase or decrease but the

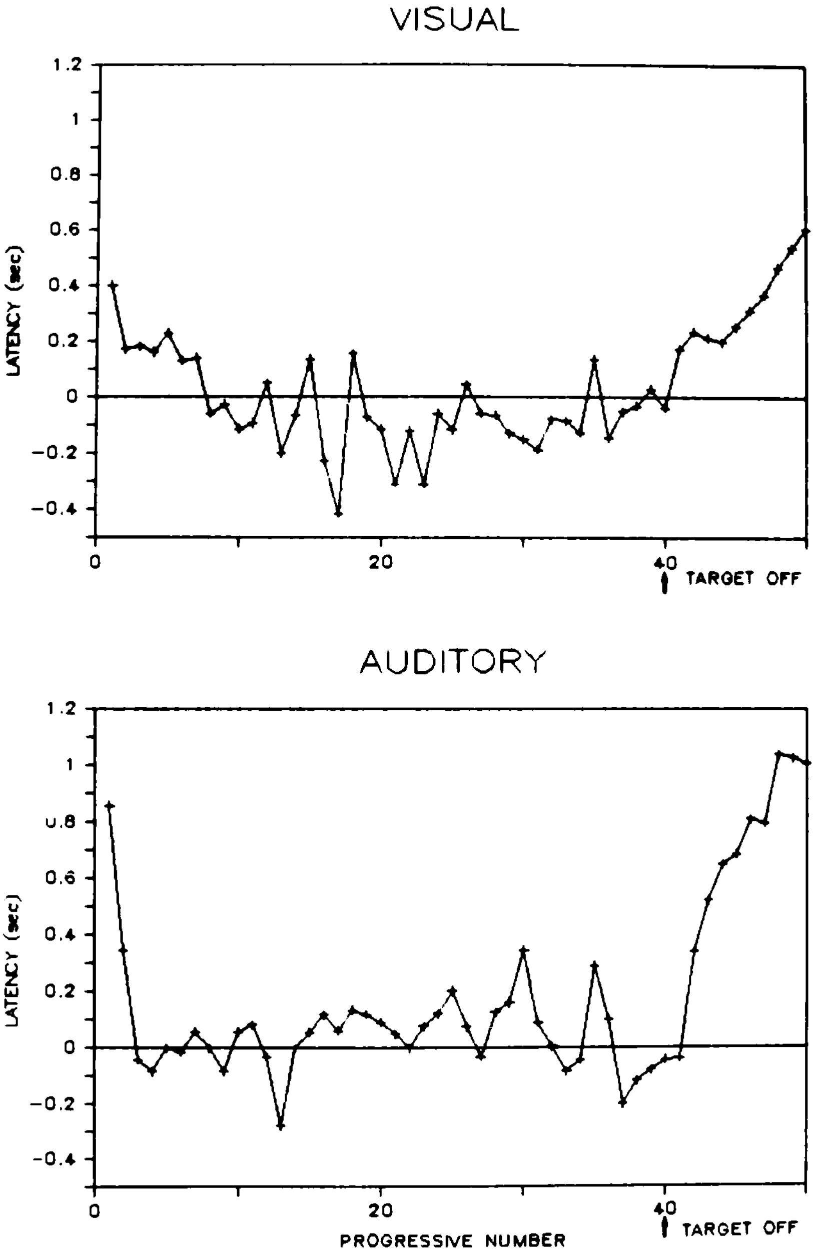

Figure 1
Time course of saccade latency in one subject tracking a square wave pattern of a visual (upper diagram) and an auditory (lower diagram) target at 0.5 Hz. Arrows indicate the instant of target disappearance.

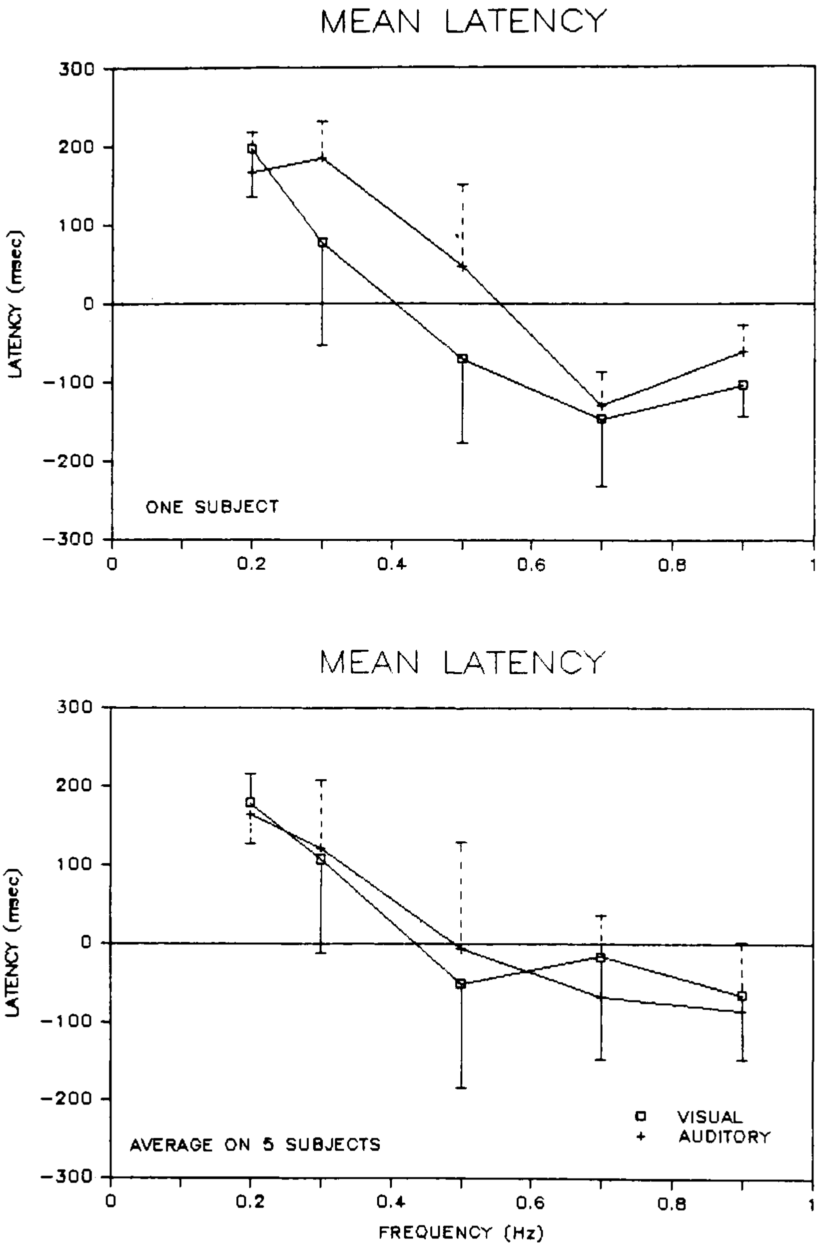

Figure 2
Mean steady state latency versus target frequency in both visual and auditory responses. Upper diagram: mean values and S.D. computed from one subject; lower diagram: mean values and S.D. computed from the population of subjects.

rate of change was almost constant in both cases. Fig. 1 shows an example in which the latency increased in both the visual and auditory case.

The average steady state latency was assumed to represent a first index of subject learning ability at the frequency considered for target motion. Fig. 2 shows the mean steady state latency versus target frequency for visual and auditory responses. The upper diagram is from one subject whereas the lower diagram gives mean values and standard deviations for the population of subjects. Both these diagrams show a decrease of the mean steady state latency with increasing target frequency. The lowest values were reached between 0.5 and 0.9 Hz . In this range of frequencies the latency was negative. Thus, learning produced not only a full recovery of the normal latency of saccades to unpredictable targets but also anticipation of target movement. Similar results were reported for visual responses by Stark et al. (1962), Dallos and Jones (1963) and Ron (1982). In addition the results in Figs. 1 and 2 indicate that the modifications induced by target predictability on visual and auditory saccadic responses result in comparable values of the latency.

The rate of latency progressive change after stimulus disappearance can be used to estimate the frequency at which the subject was making his imaginary tracking. Its value provides an index of subjects' ability to learn and store the frequency of a periodic target motion. Fig. 3 shows the frequency of the imaginary tracking versus target frequency for all the examined subjects in both visual and auditory experiments. In visual experiments the matching was almost perfect in the whole range of frequencies. In auditory experiments, there was good matching up to 0.5 Hz. Beyond this value, subjects synchronized their imaginary tracking to a frequency lower than that of the previous target movement.

A different behavior could be observed for visual and auditory tracking in relation to the amplitude of saccadic responses. Visual responses were generally slightly hypometric whereas auditory responses were clearly hypermetric. Eye displacements three fold greater than target displacement could sometimes be observed. Fig.4 shows the results from one subject. The values here reported correspond to the total amplitude of each response (primary saccade plus corrective saccades, if any). The amplitude of visual responses was almost constant from the very first cycles, whereas the amplitude of the auditory responses increased during the first cycles and then started oscillating around a value which represented an overestimation of target displacement.

During the five cycles that followed visual tracking the amplitude of saccades increased up to values close to those observed in auditory responses. The latter, by contrast, did not change after target disappearance. This evolution of saccade amplitude throughout a session was observed in all the experiments regardless of the frequency of target movement.

By using the criterion defined in the methods to distinguish between single and multiple saccade responses, the results reported in Fig. 5 were obtained. The percentage of single saccadic responses is plotted versus target frequency. By making a comparison with the results reported for saccades to unpredictable targets [Zambarbieri et al. (1982)], a significant increase of the percentage of single saccade responses can be noted for comparable target eccentricities. No correlation could be found with the frequency of target motion, and therefore with the reduction of saccade latency.

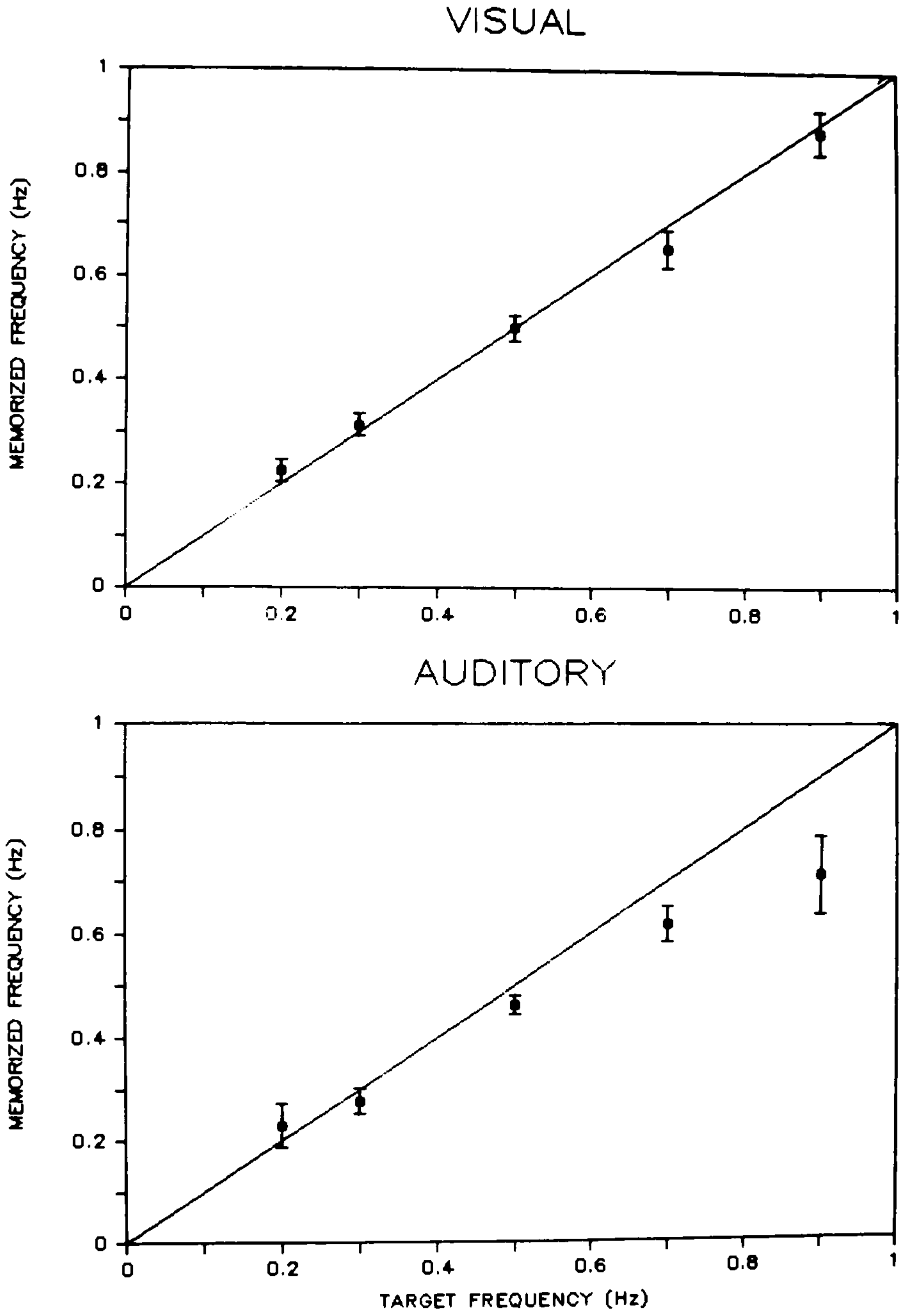

Figure 3

Mean values and standard deviations of the memorized frequency versus target frequency computed from the population of subjects after visual (upper diagram) and auditory tracking (lower diagram).

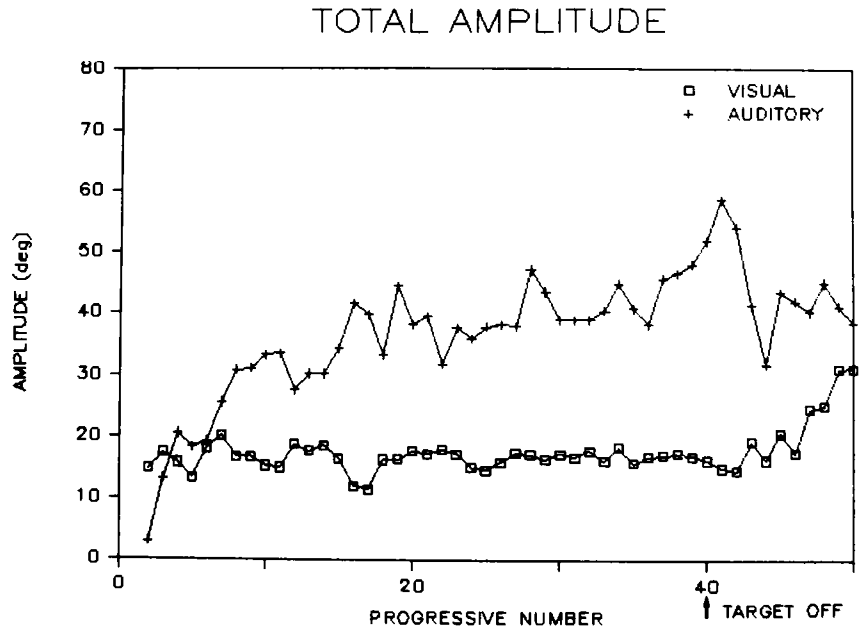

Figure 4
Time course of the total amplitude of saccade responses in one subject for a 0.5 Hz visual and auditory target movement. Arrows indicate the instant of target disappearance.

DISCUSSION

In a previous study dealing with the latency and the accuracy of saccades to visual and auditory targets presented in a random way, a number of significant differences were found between visual and auditory saccadic responses [Zambarbieri et al., 1982]. The results of that study can be summarized as follow.

1) For any target eccentricity the latency was greater for acoustically than for visually evoked saccades.
2) The latency of visual responses did not change significantly with target eccentricity, whereas the latency of auditory responses decreased with increasing target eccentricity.
3) The percentage of multiple saccade responses increased with target eccentricity for both visual and auditory responses. For large eccentricities multiple saccade responses were less frequent in the auditory than in the visual case.
4) For any target eccentricity the accuracy of auditory responses was comparable with that of visual responses.

Since in that study subjects were asked to pay as much attention as possible to the accuracy of their responses, it was concluded that the longer latency of auditory responses had to be related to the complexity of the central processing needed to reconstruct target position from auditory information [Schmid, Magenes and Zambarbieri (1982)]. An estimate of target position as accurate as in the visual case can be obtained but with longer processing time. Since sound localization is based on the differences in phase and intensity of the signals received by the two ears, a decrease of latency with increasing target eccentricity

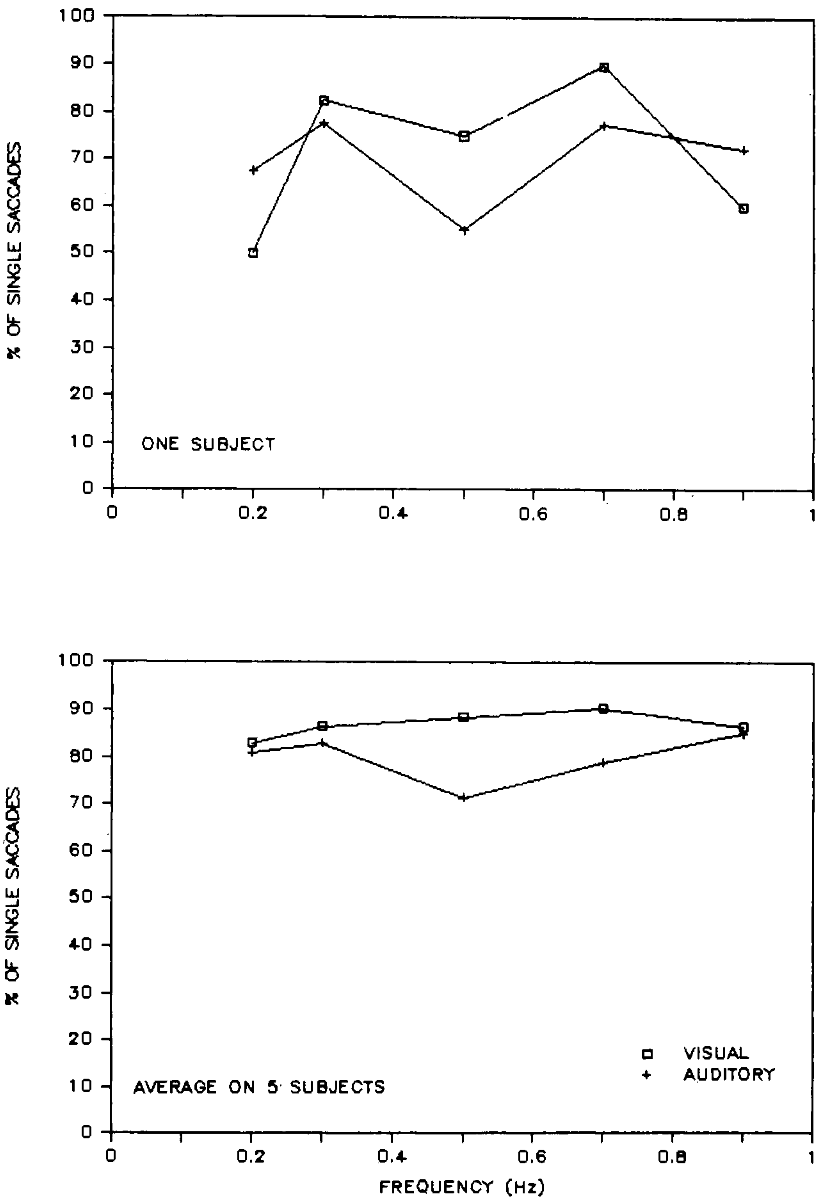

Figure 5
Percentage of single saccade responses versus target frequency computed for one subject (upper diagram) and for the population of subjects (lower diagram) in both visual and auditory tracking experiments.

could be expected in the auditory case.

In the present study targets were presented in a predictable way and subjects were not asked to pay particular attention to the accuracy of fixation. In these conditions a progressive decrease of latency was observed in both visual and auditory responses suggesting that a learning process was taking place in both cases. The buildup of learning, the steady state values of latency and their dependence on the frequency of target motion were perfectly comparable. The only significant difference was observed in the amplitude of eye movement compared to target displacement. Visual responses were fairly accurate, whereas auditory responses were highly hypermetric. The percentage of single saccade responses was extremely high in both cases.

The progressive decrease of the phase shift between eye and target movement during both visual and auditory tracking indicates that subjects were able to learn the temporal characteristics of target motion. As a matter of fact, the synchronism of eye movement can be controlled under closed loop conditions in both cases. Under the assumption that an efference copy of the neural command to the oculomotor system is made available to the central nervous system, the temporal shift between eye and target movement can easily be estimated by comparing this signal with the incoming visual or auditory information. Subject's prediction ability could then be used to compensate the delay of the saccadic system and even to anticipate target movement

On the contrary the control of the amplitude of eye movement is made during visual and auditory tracking in rather different conditions. Due to the external feedback through the retina, the fixation of a visual target is made under closed loop conditions. If a primary saccade does not bring the eyes right on the target, the residual retinal error provides information for improving fixation by a correcting saccade. This mechanism of error correction operates no matter whether the visual target is presented in a predictable or unpredictable way. A high accuracy can be obtained in both cases, and no appreciable improvement related to learning can be expected. On the other hand, it has been shown in this paper that target motion predictability leads to an increase of the percentage of single saccade responses. Moreover, visual responses that anticipate target displacement can be as accurate as those lagging behind target movement. It can therefore be concluded that during visual tracking both the timing and the amplitude of target motion can be learned. Whether they are learned through a single process that leads to the construction of an internal trace of the repetitive pattern of target motion or through distinct processes can not be established from only the results of visual tracking.

The fixation of an auditory target with the head fixed is a task performed in open loop conditions. When subjects turn their eyes toward the target, there is no feedback information about the new position of the eyes with respect to the target. The relevant parameter for the acoustic system is target position relative to subject's ears. This parameter does not change with eye movement. Thus, if target position is not accurately estimated from the incoming acoustic information through a central processing that takes a long time, the eye response will be inaccurate and no reafference information will be made available for producing corrective saccades. The short time dedicated to central processing, as demonstrated by the low values of response latency almost from the very beginning of the auditory tracking, and the absence of a feedback mechanism for correcting amplitude errors would justify the poor accuracy of the auditory responses of our subjects and the absence of a learning of the amplitude of target displacement. The high percentage of single saccade responses in the auditory case would be explained along the same lines. Since during auditory tracking only the temporal characteristics of target motion can be learned, it can be inferred that in the visual case spatial and temporal characteristics are learned separately.

This conclusion is further supported by the results of the imaginary tracking following the presentation of visual targets. After target disappearance, and therefore in open loop conditions, subjects were still able to keep the synchronism but not a correct amplitude of eye movement. Thus, timing and amplitude must have been learned and stored separately. The results of imaginary tracking also indicate that in the absence of feedback information that can be used to refresh memories, timing can be retained longer than amplitude.

In conclusion, the results reported in this paper show that subjects presented with a square wave pattern of target motion can learn its spatial and temporal characteristics through distinct processes. For each process to take place, feedback information about the relevant response error must be made available. During visual tracking this information was provided for both timing and amplitude of target motion. During the auditory tracking under the experimental conditions considered in this study only the control of timing could be accomplished in closed loop conditions. Thus, a double effect of learning could be observed during visual tracking, whereas only an improvement of response synchronism was present during auditory tracking.

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TWO-DIMENSIONAL SACCADIC AND SMOOTH PURSUIT RESPONSE TO AN EXTRAFOVEAL SMOOTH MOVEMENT

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Previous studies indicate that, in response to a step-ramp stimulus, saccade jumps do not use target velocity information or information about pursuit. We assumed that the saccadic system does not have enough time to calculate target velocity and therefore it cannot predict target location at the end of the saccade. To test our hypothesis, subjects fixated at a target on the horizontal axis for several seconds after which the target jumped up 20 degrees to the right to a predetermined eccentricity from the eye position and moved at fixed velocity down 40 degrees. At some specific position on the vertical axis an auditory signal was delivered, indicating the subject to track the target. The results show that the rate of the saccade amplitude increase was closer to the rate of the error at saccade onset than to the rate of the error 100 msec prior to the saccade onset.

INTRODUCTION

When a step-ramp stimulus is instantaneously displayed, the response is a delayed step-ramp movement. It has been thought that the saccadic system estimates the position error at the time that the saccade actually occurs (Carpenter (1977)). To approximate the error, the saccadic system has to estimate target position at the time of its onset or at the end of the saccade based on target step and ramp velocity. This error is different to the error sampled at some latency period after the stimulus presentation. When ramp velocity changed, the saccades' final position approximated the target position well at that time (Barmack (1970); Robinson (1965)). Several suggestions have been put forward to explain how the saccadic system predicts target position. Fuchs (1971) suggested that in order for the saccadic system to estimate the error accurately, it must extract some information about ramp velocity. Robinson (1973) wrote that "clearly the brain is clever enough to lead the target as a hunter leads a moving target with his gun. The saccade is not made to where the target was, but to where it will be in 0.2 sec. This amount is estimated by multiplying target velocity by 0.2 sec". Furthermore, because of the difference in the latency response of the saccadic and smooth pursuit systems, for the saccadic system to accurately estimate the error at time of saccade onset it must have information, not only of target velocity, but also of the smooth pursuit system. This would imply that stimulus ramp velocity is available to the saccade system.

In a recent paper, Heywood and Churcher (1980) pointed out that the error estimated by the saccadic system might not be predictive in the strict sense: "for human subjects at least, knowledge of the task situation may lead to the adoption of response strategies that are 'predictive' in the sense that they allow the task to be performed with improved accuracy, yet do not involve prediction in the sense of extrapolation of velocity at all". Such a strategy might 'appear' to be predictive yet base the saccadic jump on sheer expectation rather than on extracting target velocity. Furthermore, because of the difference in the latency response of the saccadic and smooth pursuit systems, for the saccadic system to accurately estimate the error at time of saccadic onset it must have information, not only of target velocity but also of the smooth pursuit system. Since visual information relevant to saccade execution seems to be unavailable within 80-100 msec immediately preceding the onset (Wheeless, Boynton and Cohen (1966); Komoda, Festinger, Phillips, Duckworth and Young (1973); Becker (1975)) these authors proposed that the error to the saccadic system was based on a position error sampled at 100 msec before the onset of the saccade. Heywood and Churcher's data indicate that the saccade amplitude changes with target velocity at the same rate (in a naive subject) as the error in position 100 msec before the saccade onset. In experienced subjects these authors suggest that the saccade amplitude is between the error at saccade onset and the error 100 msec prior to saccade onset. They have also shown that the total distance travelled by the target at the time of the saccade end (for same steps with different ramp velocities) is only weakly correlated with saccade amplitude. The latter finding reinforced the notion that saccade jumps to step-ramp targets do not use (or use very little) target velocity information or information about pursuit.

The question of whether velocity information or information about pursuit is actually used by the saccadic system prompted us to re-examine the question of saccadic prediction. Our basic hypothesis was that in a step-ramp paradigm, the saccadic system does not have enough time to calculate target velocity and therefore it cannot predict target location at the onset or at the end of the saccade. Assuming a response delay of 250 msec, if the decision to jump is made 100 msec before the onset of the movement, only 150 msec are left for the saccadic system to extract information concerning velocity. Taking into consideration the delay of the visual system, this is indeed a very short time.

METHOD AND RESULTS

To test our hypothesis we designed a paradigm in which visual input was available to the subject before he was requested to respond to target displacement. The eyes fixated at a laser dot on a screen on the horizontal axis. After several seconds, the target jumped up 20 degrees and moved at fixed velocity down 40 degrees with some pre-determined eccentricity from the eye position on the horizontal axis (Fig. 1,A). At some specific position on the vertical axis, the target triggered an amplifier which delivered a signal to a loudspeaker heard by the subject as a click. The subject was asked to remain still at his first fixation site and then, once he heard the auditory signal he was asked to track the target as fast and as accurately as possible. If saccades do take target movement into consideration one may expect the saccadic system to predict target position and jump on the vertical axis at time 't_0', where the target would be at the beginning or at the end of the execution of the saccade (Fig. 1,A). If, however, the saccadic system samples the position error 100 msec before saccade onset, the saccadic jump would be at the site where the target was at time 't_0-100'. The time course of the target and the eye movements are illustrated diagrammatically in Fig. 1,B. Eye movements were measured using a scleral coil technique. Vertical target velocity, site of auditory stimulus and horizontal eccentricity were randomized. The data from 5 subjects were analyzed by computer.

Following the presentation of a down moving target, three typical responses are shown in Fig. 2. The top tracings are an example of an eye movement response separated on the horizontal and vertical axes. On the non-tracking axis the saccade was usually hypometric and was followed by a correcting saccade (Fig. 2, left panel). For a 10 degree eccentricity the mean saccade correction was 1.1 degrees, increasing only slightly to 1.3 degrees for a 20 degree stimulus eccentricity. On

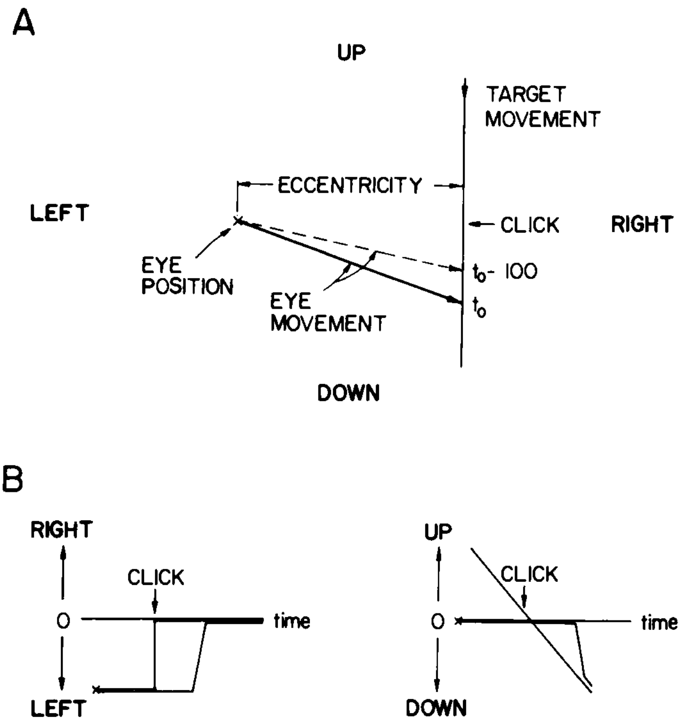

Figure 1
A diagrammatic presentation of the paradigm used. A) A two dimensional diagram showing the initial eye position (at a laser dot) and, following the target jump to the right and up, target moved down at fixed velocity (5 to 30 deg/sec). At some predetermined site (on the horizontal axis, 5 deg up or 5 deg down) an auditory stimulus was delivered. The two vectors representing eye movement are two possible saccadic jumps, depending on whether the saccadic movement was based only on position error (broken line) or whether the saccade also had information of target velocity (continuous line). B) The time course of the target and the saccadic response on the non-tracking axis (left) or the tracking axis (right).

the tracking axis (Fig. 2 right panel) the mean saccade correction was very small (0.02 degrees). Occasionally, while the subject was fixating at an imaginary target before the auditory stimulus was delivered, the eyes drifted on one or both axes (Fig. 2,B). On the non-tracking axis the drift movement was in the opposite direction to that of the target jump. When drift was present it was 0.5 to 1 deg/sec and was independent of eccentricity or target velocity. On the tracking axis the drift (1-5 deg/sec) was in the same direction as target movement and was only slightly correlated to target velocity (correlation 0.28). The saccade direction was dependent on the position of the target when the auditory stimulus was given, and on the accumulated drift at the last position at which the error was

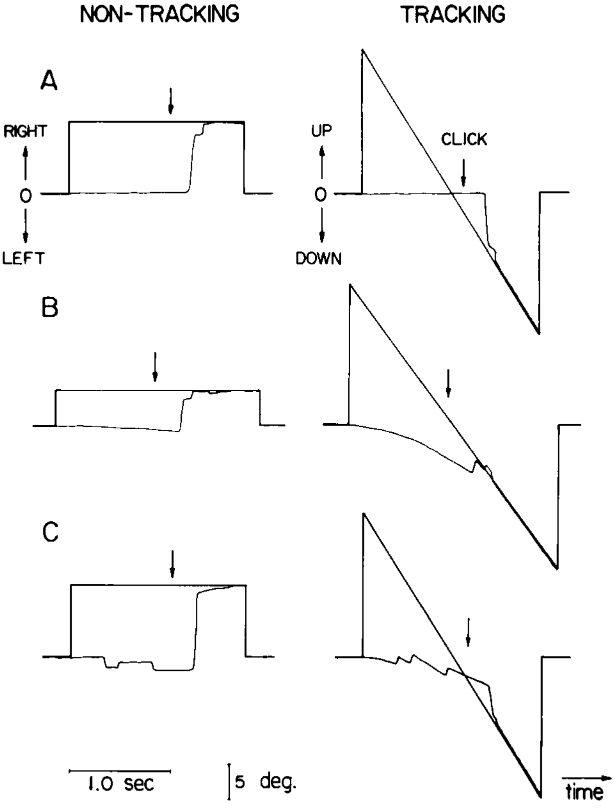

Figure 2
Three examples of eye movement response separated on the horizontal (non-tracking) and on the vertical (tracking) axis.
A) The tracking of eye movements most commonly recorded.
B) Some subjects tended to develop a drift on both axes, and
C) drift which developed to small nystagmus-like trajectory.

sampled by the saccadic system prior to the saccade onset. The drift in some of the eye movement responses developed to a small nystagmus-like trajectory (Fig. 2,C).

The smooth pursuit response has a delay of 125 msec whereas the saccade response has a delay of about 200 msec. Following the auditory stimulus, the oculomotor system was presented with the task of responding to a jump and a smooth moving target on different axes. The results indicate that the eye movements on the two axes synchronized and the latency on the two axes was not found to be statistically different (F=1.68, p>0.1). Following the auditory stimulus, the saccade latency slightly decreased as stimulus velocity increased (LAT= -0.5*VEL+336). Our results agree with Heywood and Churcher's (1980) data where response latency was not found to be dependent on stimulus velocity in two of the three subjects although in their study the mean latency was much smaller (195 to 280 msec in three different subjects). The longer latency in our data might better be compared to the saccade latency evoked by the presentation of an auditory target in the dark (250-350 msec, depending on target position, Zambarbieri (1982)). The mean latency for the secondary (correcting) saccade was 230 msec and was not dependent on target velocity.

The saccade amplitude was dependent, not only on stimulus velocity, but also on the time when the auditory stimulus was delivered on the vertical axis. When the stimulus was at the level of the horizontal axis, the correlation of saccade amplitude to stimulus velocity was 0.68 (Fig. 3). This has been shown previously (Heywood and Churcher (1980)) and it does not indicate whether the saccade amplitude takes ramp stimulus velocity into consideration. To study this question we

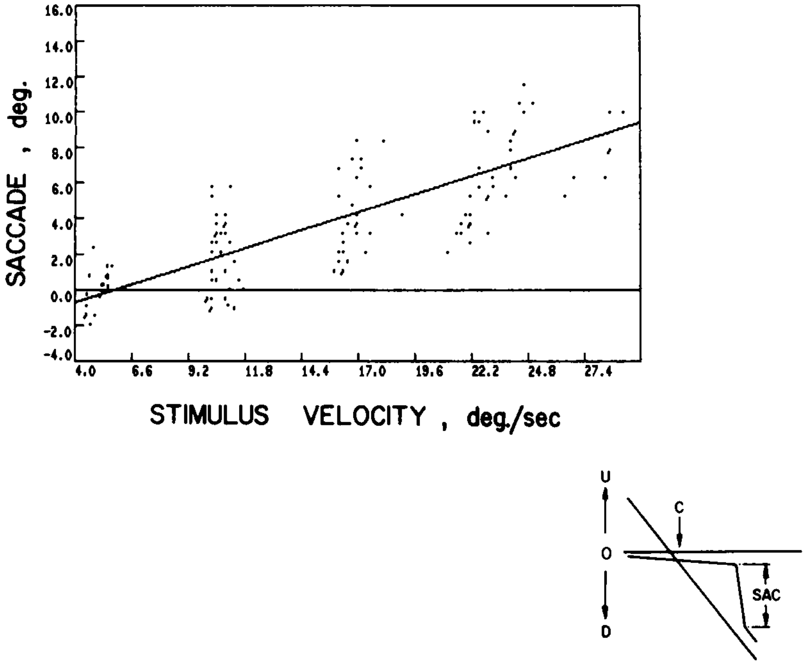

Figure 3
The saccadic amplitude dependence on stimulus velocity. The auditory stimulus was delivered when the target was at the level of the horizontal axis. Also shown is the saccadic linear regression on stimulus velocity.

measured the saccadic response (SAC, Fig. 4), the expected movement (total distance travelled by the target at the end of the saccade, EXP.MOV), the error at the saccade onset (E_0) and the error 100 msec prior to the saccade onset (E_{100}). Drift was taken into consideration by adding it to the corresponding variables: B_0 at saccade onset and B_{100} msec prior to the saccade onset. The linear regressions of these 4 variables were computed and plotted in Fig. 4. The rate of the saccade amplitude (B_0+SAC) increase was closer to the rate of the error at saccade onset (B_0+E_0) than to the rate of the error 100 msec prior to the saccade onset ($E_{100}+B_{100}$). Since the drift displacement could be non-linear we plotted the same

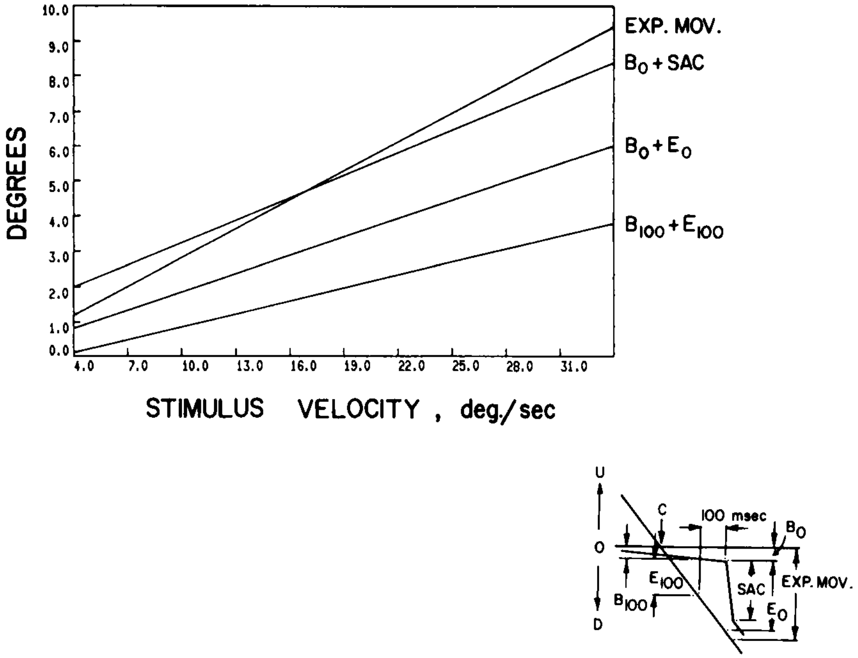

Figure 4
The linear regression line of 4 dependent variables on stimulus velocity. The auditory stimulus was delivered when the target was at the level of the horizontal axis. The measured responses shown in the inset were saccades and drift at saccade onset (B_0+SAC), total distance travelled by the target at the end of the saccade (EXP.MOV.), the error and the drift 100 msec prior to the saccade onset ($B_{100}+E_{100}$) and the error and the drift at the saccade onset (B_0+E_0).

parameters with respect to the relative error at the end of the saccade (REM). The linear regression of saccade amplitude on REM is shown in Fig. 5 (SAC=0.87* REM+0.03). Similarly, we computed the linear regression of the error at saccade onset (E_0)(E_0=0.85*REM-1.6) and the regression of the error 100 msec before saccade onset (E_{100})(E_{100}=0.8*REM-2.45). The slope of the regression of SAC was closer to E_0 than to E_{100}. All three linear regressions had a correlation coefficient between their respective variables higher than 0.9.

DISCUSSION

In everyday life we are often faced with a situation in which the oculomotor system is required to respond with a saccade to an extrafoveal moving object. Such a saccade might be made, for example, to look suddenly at a moving object in the visual field or to look at a site where a thrown object will fall. If the saccade is to predict the visual error at the time that the saccade actually occurs it must have access to pursuit information. Yet, a recent study (Heywood and Churcher (1980)), failed to support the contention that saccades make full use of velocity information. Their data is compatible with the hypothesis that saccadic

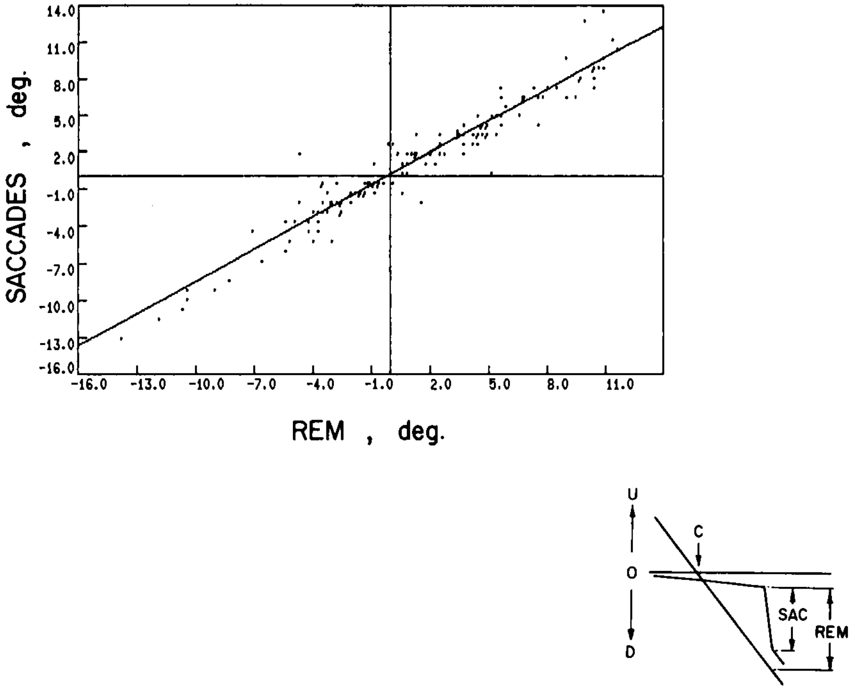

Figure 5
The saccade amplitude dependence on the relative expected movement (REM, shown in the inset). The linear regression line is also shown.

amplitude is based upon position error and that this error is probably sampled for the last time about 100 msec prior to the saccade onset.

In our study we assumed that to respond to a step-ramp target motion, the saccadic system has very little time to compute target velocity information. A paradigm closer to natural conditions would be to provide the saccadic system with enough time to extract this information. We have, therefore, allowed the subject to see the target extrafoveally for various periods of time (0.5-4 sec) before the auditory stimulus to make a saccade. Our data indicate that seeing the moving stimulus for even 0.5 sec was enough for the saccade to predict the visual error at the time the saccade actually occurred. The target was seen for a longer period if we add to the time prior to the auditory stimulus at least part of the relatively long reaction time (320-350 msec). The reaction time was similar to the saccadic response time to an auditory stimulus (Zambarbieri (1982)). Our naive subjects performed individually in a similar manner, in the sense that their saccades seemed to correct the error at saccade onset, not only for position but also for pursuit movement. This correction probably does not require access to the saccade generator as correction at saccade end would have required.

Our data differ from Heywood and Churcher's (1980) results with respect to at least two more findings. Their results show that as ramp velocity increased, the difference became larger between the expected movement at saccade end (EXP.MOV.) and saccade amplitude (SAC) (Fig. 3,A in Heywood and Churcher (1980)). Furthermore, in a naive subject the saccade amplitude was always smaller than the error 100 msec before saccade onset. Having apparently enough time to estimate the stimulus velocity, the saccade amplitude was longer than the error 100 msec prior to saccade onset (E_{100}) or the error at saccade onset (E_0) and it approximated the expected movement (EXP.MOV.) more correctly at saccade end (B_0+SAC) (Fig. 4). An additional possible explanation for the two sets of results could be the different step size stimulus used (1.75 deg versus 5 deg in this study). Whether this leads the subject to adopt different strategies resulting in different patterns of eye movements requires additional investigation.

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GAZE-POSITION DEPENDENCE OF SACCADIC LATENCY AND ACCURACY

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INTRODUCTION

Some papers note that the latency of saccadic eye movements slightly increases with the size of the target displacement (Zambarbieri, Schmid, Magenes and Prablanc, 1982). Others (Findlay, 1983) find no latency increase up to 20 deg.

Generally, the reported experiments were executed by moving the target from the primary position of the gaze toward the periphery (centrifugal saccades). Therefore, the relation between latency and target displacement which has been found could alternatively be due to a dependence of the response on the target position with respect to the head, i.e. in craniotopic coordinates, rather than on the target position in retinotopic ones.

A clear knowledge of a possible gaze-position dependence of saccadic latency and accuracy is essential in understanding the central mechanisms responsible for the generation of saccadic commands as well as their possible levels of action.

METHODS

Twenty subjects, kept in darkness, were asked to follow a dot visual target either with maximum velocity or maximum accuracy. The target moved randomly in time, with jumps of random amplitude in a range of +/-35 deg in the horizontal plane.

EXPERIMENTAL RESULTS AND DISCUSSION

The mean latency of the main saccadic responses ranged from 136 ms to 208 ms, with a mean intersubject value of 173 ms +/- 18 SD, when subjects were asked to follow the moving target with maximum velocity, and ranged from 182 ms to 219 ms, with a mean intersubject value of 206 ms +/- 13 SD, when they were asked to follow the target with maximum accuracy. With the second paradigm, all the subjects had high latencies, while with the first one many subjects were able to exhibit lower latencies.

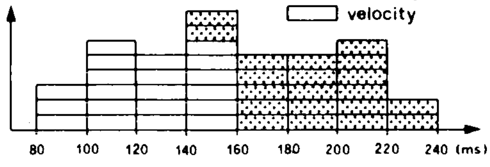


Fig.1

The distribution of the spreads of the latencies for each subject, given as 4 SD from the individual values (97% probability) is given in Fig.1. The spreads with the second paradigm were about twice those with the first one.

For each subject, the latency of the saccades to the right was different from that of the saccades to the left. The distribution of the deviations between mean latency to the right and mean latency to the left for all the examined subjects, with both the two paradigms, is shown in Fig.2. No differences between the two paradigms were found.

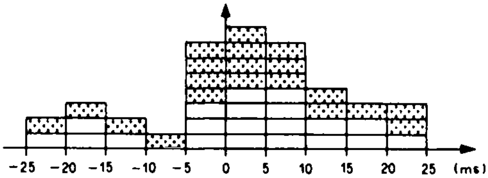
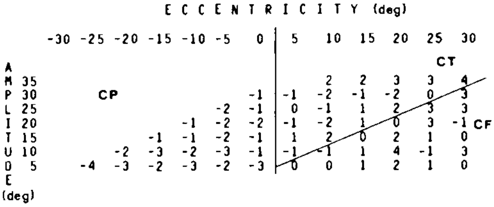


Fig.2

To study the way latency depends on starting target position, ending target position and amplitude of target displacement, a normalized bidimensional graph of the weighted mean values related to all the subjects was built up.

The graph of Fig.3 represents the values 5D(e,a), as a function of the final target eccentricity (e) and of the amplitude of target displacement (a), where D(e,a) is an adimensional function evaluated as the weighted averaged deviation of latency values at e,a from the individual mean values, and it is evaluated as:



AMPLITUDE (deg) \ ECCENTRICITY (deg)	-30	-25	-20	-15	-10	-5	0	5	10	15	20	25	30
35									2	2	3	3	4
30							-1	-1	-2	-1	-2	0	3
25						-2	-1	0	-1	1	2	3	3
20					-1	-2	-2	-1	-2	1	0	3	-1
15				-1	-1	-2	-1	1	2	0	2	1	0
10			-2	-3	-2	-3	-1	-1	-1	1	4	-1	3
5		-4	-3	-2	-3	-2	-3	0	0	1	2	1	0

Fig.3

$$D(e,a) = \frac{\sum_{i=1}^{n}\left[\frac{M_{L_i}(e,a)-\bar{M}_{L_i}}{\bar{S}_{L_i}}\, n_{L_i}(e,a) + \frac{M_{R_i}(e,a)-\bar{M}_{R_i}}{\bar{S}_{R_i}}\, n_{R_i}(e,a)\right]}{N(e,a)}$$

where M_{L_i} (e,a) and n_{L_i}(e,a), and M_{R_i} (e,a) and n_{R_i}(e,a) are the mean latencies and the numbers of occurrences of the i-th subject, for the saccades to the left and to the right, respectively, at the coordinates e,a; $\bar{M}_{L_i}$ and $\bar{S}_{L_i}$, and $\bar{M}_{R_i}$ and $\bar{S}_{R_i}$ are the global mean values and standard deviations of the i-th subject, to the left and to the right.

$N(e,a) = \sum_{1}^{n} (n_{L_i}(e,a)+n_{R_i}(e,a))$ is the total number of occurrences at e,a for the n subjects.

The abscissa e is the final target position, with the negative sign for centripetal displacements and positive sign for centrifugal ones, including those which cross the centre (central movements).

The mean value (-2+/-.9) calculated for centripetal movements (CP) results much lower than that calculated for centrifugal ones (CF) (1.1+/-1.5); central movements (CT) present an intermediate value (0.6+/-1.8), which is closer to the centrifugal one.

The graphs in Fig.4 and 5 have been drawn from the map of Fig.3.

Fig.4 shows the dependence of the latency on the initial and final eccentricities; the ordinates D are mean deviation values evaluated for each eccentricity, as averages over all the amplitudes. Both the graphs show clear monotonic relations between latency and eccentricity. They are roughly translated by 20 deg from each other, indicating a very weak relation of the amplitude on latency, each point of these graphs corresponding to a mean amplitude of 20 deg.

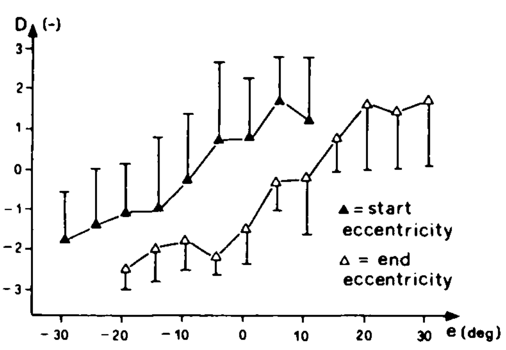


Fig.4

Moreover, the graphs of Fig.5 indicate that the final, rather than the initial eccentricity influences the saccadic latency. Fig.5 shows the mean dependence of the latency on the amplitude. The ordinates D are mean deviation values, evaluated, for each amplitude, as average over all the final eccentricities (continuous lines) or over all centrifugal and central saccades (dashed lines). The second graph, which does not contain the contribution of centripetal saccades, represents values which are homogeneously weighted with respect to the final eccentricity, but not with respect to the initial one. It shows, despite some oscillations, no relation between latency and amplitude, up to 30 deg, indicating indeed a dependence of the latency only on the final eccentricity, for displacements up to 30 deg. Over this amplitude, as can be seen also from Fig.3, the latencies abruptly increase, whatever the eccentricity.

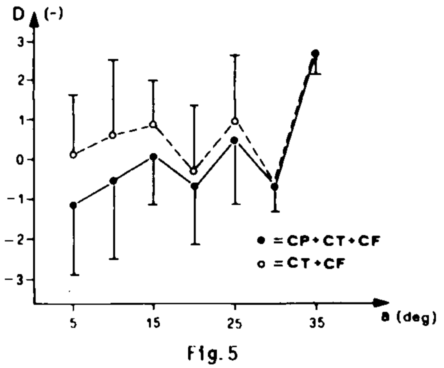
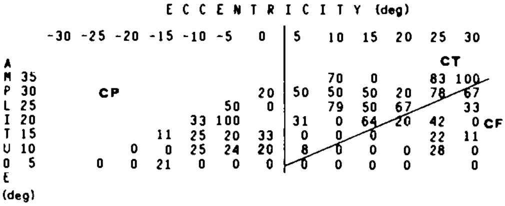


Fig.5

We studied the accuracy of the main saccades as the probability of having corrective saccades. The bidimensional map in Fig.6 represents the percent probability P(e,a) of occurrence of a corrective saccade at the coordinates e,a, weighted and averaged in the same way as above for D(e,a). Although lacking data at many coordinates (only subjects having a lot of corrective saccades have been used), the map shows that accuracy is mainly dependent on the amplitude of the displacement. However, centripetal saccades show lower accuracy (or, perhaps, simply higher probability of the corrective saccades) for intermediate amplitudes.



E C C E N T R I C I T Y (deg)

AMPLITUDE (deg)	-30	-25	-20	-15	-10	-5	0	5	10	15	20	25	30
												CT	
35									70	0		83	100
30	CP						20	50	50	50	20	78	67
25						50	0		79	50	67		33
20					33	100		31	0	64	20	42	0 CF
15				11	25	20	33	0	0	0		22	11
10			0	0	25	24	20	8	0	0	0	28	0
5		0	0	21	0	0	0	0	0	0	0		0

Fig.6

CONCLUSIONS

From these results, we can conclude that latency variations, previously thought of as being due to the amplitude of the target displacement, and therefore to some processing in retinotopic maps, are instead due to the final target eccentricity. This does not mean simply that they are related to processing in craniotopic maps, since not only the final position in craniotopic coordinates, but mainly the direction from which this position is reached (from a more central or a more eccentric position) is determinant.

No strong influence on saccadic accuracy can be ascribed to gaze position.

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COMPARISON BETWEEN PSYCHOPHYSICAL AND SACCADIC RESPONSES TO NEAR THRESHOLD VISUAL STIMULI

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INTRODUCTION

Can spatio-temporal properties of the visual system, as determined by psychophysical measurements, be used to describe the probability of evoking a correct saccadic eye movement?

It is known from psychophysical experiments that for stimuli up to a certain duration there exists an inverse relationship between contrast detection threshold and stimulus duration.

The interval of this linear summation has been shown to be about 60 ms for luminance contrast stimuli and about 200 ms for chromatic stimuli equiluminant to the visual field.

In our experiment this dependence was examined for saccadic eye movements.

METHODS

eye movements of the binocularly viewing observer are recorded by EOG (0.5 deg. accuracy).

background: a yellow 50 deg. wide T.V. screen. Wavelength 583 nm, luminance 21.6 cd/m**2.

stimulus: a square (1.5 deg. wide) 15 deg. left or right of the central fixation spot. The wavelength, the luminance and the duration can be changed independently

procedure: in psychophysical measurements contrast detection thresholds are determined by the method of limits.

For saccadic measurements the observer had to respond by making a saccade to the stimulus at every stimulus presentation.

The contrast detection threshold is defined as the contrast at which 80% of the responses are correct.

CONCLUSIONS

The probability of evoking a correct saccade depends in a quantitatively similar way on the duration of a stimulus as the contrast detection threshold in psychophysical experiments, both for luminance contrast stimuli and for chromatic stimuli.

Spatio-temporal properties of visual stimuli affect saccadic responses in the same way as has been established for psychophysical responses.

Latency of saccades to luminance contrast stimuli is about the same as the latency to chromatic stimuli in spite of a difference of 140 ms in the linear summation intervals.

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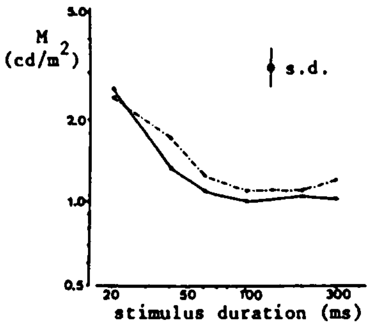
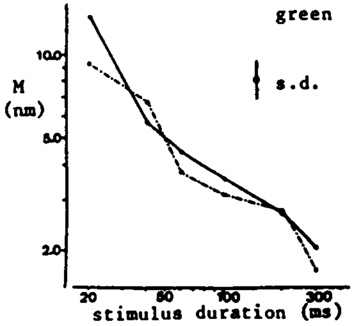
RESULTS

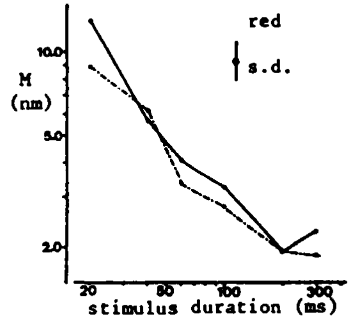
luminance contrast stimuli



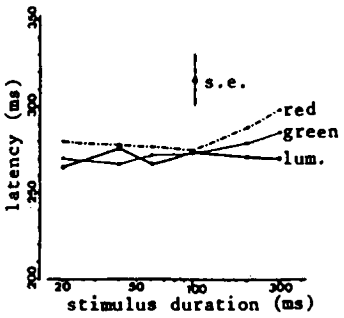
The contrast detection threshold M is plotted against the stimulus duration for the psychophysical measurements (-·-·-·-·-) and the saccadic measurements (———).

chromatic stimuli





latency



The averaged latency of saccades to stimuli at threshold level is plotted against the stimulus duration for luminance contrast stimuli and chromatic (red and green) stimuli.

Saccadic Velocity Varies as a Function of 'Activation'

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1. Problem

There are several factors reported, which influence it: darkness, fatigue, tranquilizers, alcohol and so on. How and where do these different factors work? Surely, they do not influence the nervous system as a whole, but also surely not very specifically only the oculomotor system, but somewhere in between. It is reasonable to assume that these factors influence a yet not well understood system *'activation'*. In the psychological literature activation is said to be influenced by *mental effort, short term habituation, time on task* . So, we looked at saccadic velocity as a function of these behavioral conditions that modulate arousal.

2. Methods

Sixteen subjects, all students or members of our lab, looked as closely as possible on an oscilloscope at a jumping light spot. The spot jumped horizontally across twenty degrees in successively shorter intervals (i.e. increasing stimulus frequency .1-1.2 Hz). Trials 1-6 involved no additional work; trials 7-9 involved simultaneous mental arithmetic. Stimulus sequence and dc-EOG were recorded on magnetic tape with a total bandwith of 50 cps and processed off-line on a minicomputer. Identified saccades were defined as *response saccades* when they were bigger than half of the stimulus jump, occurred between the preceding and the following jumping interval, went in the same direction as the stimulus, and occurred not later than 330 ms after the stimulus jumped. Only response saccades are further considered here. For some purposes the response saccades were divided into *reactive and anticipatory response saccades* as defined by a limit of 130 ms after the stimulus jumped. The *velocity* of response saccades was taken from their calculated 18°-amplitude, if their original amplitude had a value inside the window 18° +- 4°. Most values here shown are grand means of all Ss. divided into 12 or fewer frequencies of stimulus jumping.

3. Results

Saccadic velocity varies as a function of some task variables.

a) During the trials saccadic velocity decreased first and increased later on.(Figure 1 Trials 1-3). Our interpretation: *the decreasing is due to short term habituation, the increasing is due to the increasing mental effort, which arose when the stimulus moved faster and faster.*

b) When Ss. had to look and simultaneously do mental arithmetic, saccadic velocities increased (Figure 1 Trials 7-9).

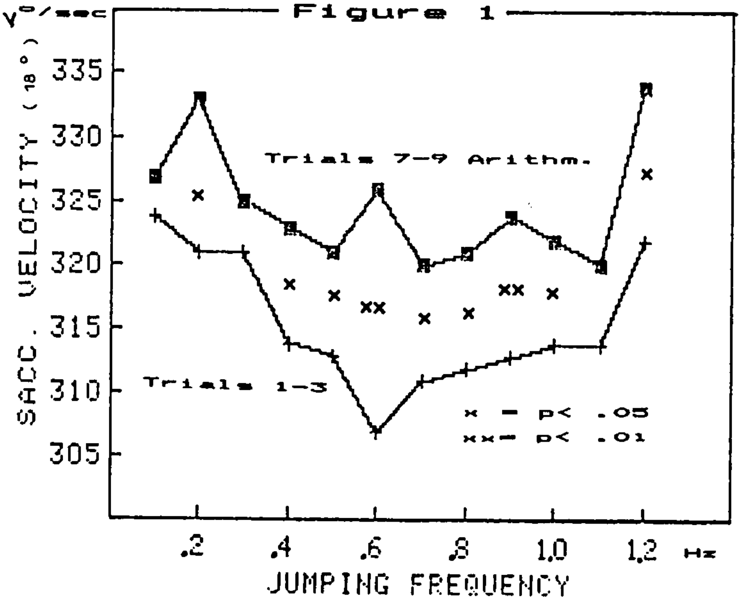
Figure 1

c) Reactive and anticipatory response saccades: Anticipatory saccades tended to be a little slower than reactive ones. (Figure 2).

To have a closer look at this effect we only summed events when a subject went from reactive (= event 0 in figure 3) to anticipatory behavior (event 1 and 2 in figure 3) or from anticipatory (0) to reactive (1,2): in these *event windows* saccadic velocity shows the expected trend, increasing from anticipatory to reactive behavior and decreasing from reactive to anticipatory in all stimulus frequency ranges. (Figure 3). Most transitions from event zero to event one were accompanied by significant velocity changes.

4. Discussion

It was shown that saccadic velocity varies as a function of subtle factors known to influence activation, so the conclusion is that *changing saccadic velocity reflects changing activation.* Surprising seems to be the stable initial short term habituation effect (this is our interpretation of the initial decrease in the saccadic velocity), more common is the effort effect (i.e. the increase in velocity later on, when following the fast stimulus becomes more strenous), which is seen in almost any experiment using activation indicators. The anticipation-reaction effect was described in 1984 by Bronstein & Kennard as well as by Galley independently (both in: Gale & Johnson (Eds.), Theoretical and Applied Aspects of Eye Movement Research. North Holland, Amsterdom).

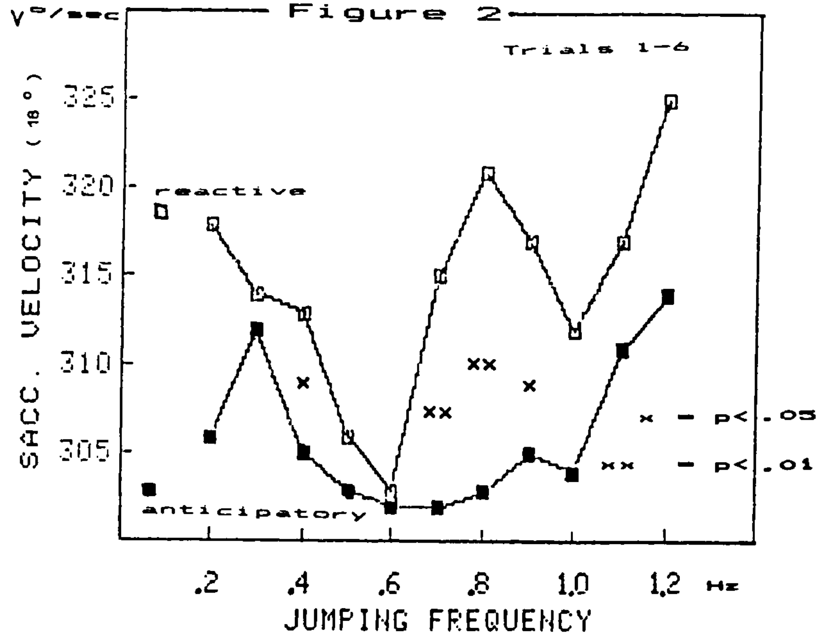
Figure 2

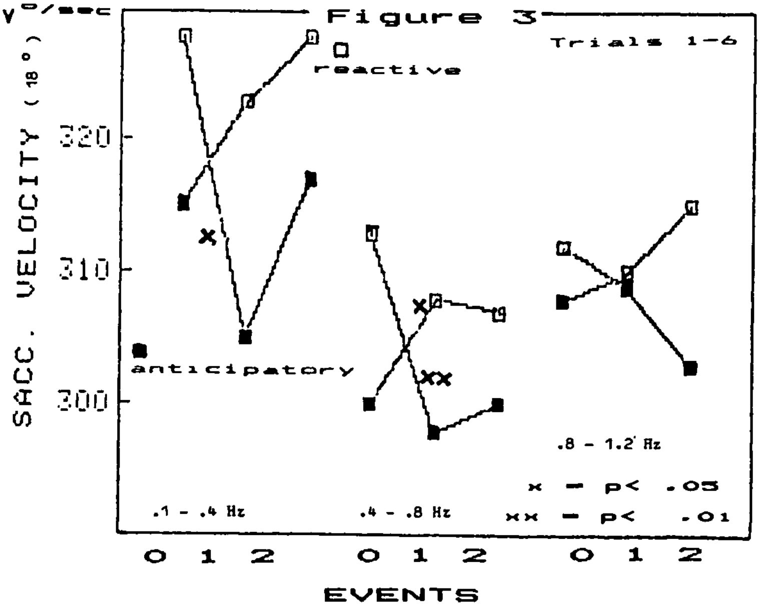
Figure 3

Here we had a closer look using the event window, when a subject changes his strategy from reactive to anticipatory and vice versa. Our interpretation is that it should normally be *more economical (i.e. needs less activation)* doing the job by using anticipation (i.e. acting out a time concept of the stimulus behavior) than by waiting until the stimulus jumps and then reacting.

THE EFFECT OF RELATIVE MOTION

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Introduction

The contrast sensitivity of the visual system is usually measured in situations where head and eye movements are eliminated as much as possible. In ordinary situations both the head and eyes are moving to a greater or lesser extent. Measurements of the visual acuity during movements of the retinal image as reported in the literature do not always give comparable results. There is a difference between the findings of those authors who prevent eye movements and those who allow them.

To check whether the contrast sensitivity function of the visual system, measured in a stationary situation, is representative for the visual performance under more dynamic circumstances, we measured the contrast sensitivity with gratings for three different viewing conditions:

- **I The fixation spot and the grating both are stationary**
- **II The fixation spot is stationary, while the grating is moving**
- **III The fixation spot and the grating both are moving**

Methods

The stimulus is a vertical sinusoidal grating with a height of 5° and a width of 10°. The fixation target is a small bright spot. Both the grating and the fixation spot are displayed on an oscilloscope screen, at 1000 frames/sec., 1000 lines/frame. The grating can be moved horizontally by changing the position of the grating by a triangle wave with a peak-to-peak amplitude of 8°.

The contrast of the grating on the detection threshold level (threshold contrast) was determined by a kind of v. Békésy tracking. The subject's task is to keep the contrast of the grating at his detection threshold by increasing and decreasing continually the contrast. For a more detailed description, see Keemink, Van der Wildt and Van Deursen (1979), Medical & Biological Enginering & Computing **17**, 371-378.

Results and Discussion

The threshold contrast is measured as a function of the stimulus velocity for several spatial frequencies of the grating (ranging from 0.2 to 12 cycles/degree). The experimental data measured with a stationary fixation target, and a moving grating **(Condition II)** are shown in Fig. 1.

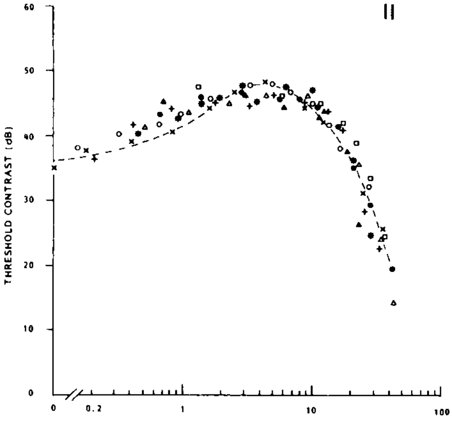

Fig. 1. The threshold contrast, for several spatial frequencies (f_s), as measured in condition II, plotted versus the velocity of the retinal image.
The vertical position of the different curves is shifted in order to obtain an optimal fit with the curve for $f_s = 1$ cycle/degree (the dashed line).

The shape of the curves for the different spatial frequencies resemble each other very much, but do not coincide. Shifting the different curves both horizontally and vertically in such a way that they all fit the curve for f_s = 1 cycle/degree (the dashed line), results in a single curve for all the different spatial frequencies. The amount of horizontal and vertical shifts are given for each frequency in Fig. 2 and Fig. 3 respectively.

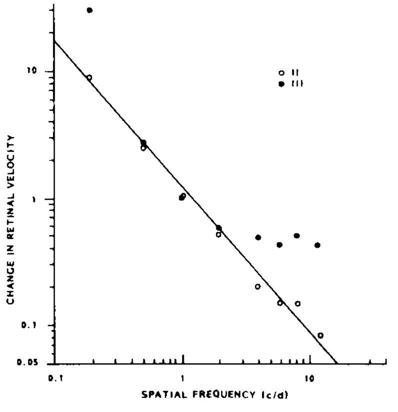

Fig. 2. The extent of the changes in the horizontal direction necessary to obtain the fit with the $f_s = 1$ c/d-curve as shown in Fig. 1 and in Fig. 4, is plotted versus the corresponding spatial frequencies.
The values plotted as open circles are related to the data as measured in condition II (Fig. 1), while the dots respresent data related with measurements in condition III (Fig. 4). For comparison a line is drawn with a slope of -1.

The open circles, representing the horizontal changes needed to fit the curves for the different spatial frequencies in Fig. 1, show that the values follow a curve with a slope of -1, that is when the spatial frequency is doubled, the necessary shift is halved. For comparison a line is drawn of which the slope is -1. This indicates that a crucial

ON CONTRAST SENSITIVITY

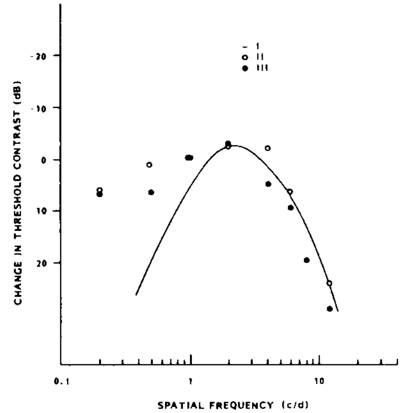

Fig. 3. The extent of change in the vertical direction to obtain the result shown in Fig. 1 and Fig. 4 are plotted versus the spatial frequency. The open circles represent data related to Fig. 1, while the dots are related to the curves in Fig. 4. The solid curve is the contrast threshold measured in condition I.

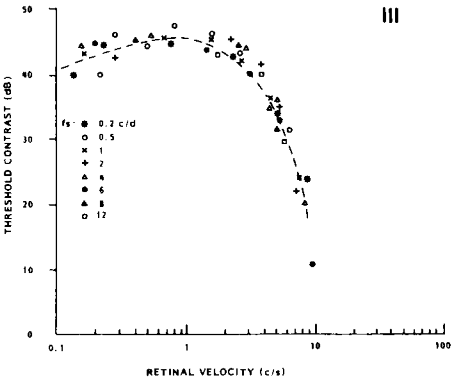

Fig. 4. The threshold contrast for several spatial frequencies (f_s), as measured in condition III, plotted versus the velocity of the retinal image. The different curves are shifted to obtain an optimal fit with the curve for $f_s = 1$ c/d (the dashed line).

parameter for the detectability of moving gratings is the retinal velocity expressed in cycles per second, which is equivalent to the temporal flicker frequency at any location of the stimulated part of the retina. The retinal velocity equals the velocity of the grating, because in situation II the eye is stationary, and only the grating is moving.

The vertical shift of the curves necessary for the fit in Fig. 1 is shown in Fig. 3.

The change in threshold contrast as a function of the spatial frequency passably resembles the contrast sensitivity function of the visual system as given in Fig. 3 as a solid curve. This curve is measured when both the eye and the grating are stationary (Condition I).

The consequence of this is that when the contrast of the grating is corrected for the influence of the spatial frequency, the threshold contrast measured with moving gratings and a stationary eye can be described by one single curve, as a function of the retinal velocity expressed in cycles/second. So the threshold contrast for moving gratings is determined too by the temporal properties of the eye, as is also reported in the literature (e.g. Burr and Ross (1982); Vision Res. **22**, 479-484).

So far the fixation target did not move. Now we tried to use the same description for situation III: a fixation target that moves along with the grating. In that case, the retinal image velocity is completely due to slip of the pursuit movements. For the amount of retinal slip as a function of the target velocity, data are used from the literature (Baloh, Kumley, Sills, Honrubia and Konrad, 1976; Annals Otology **85**, 111-119); and Schalén, L. 1980; Acta Otolaryngol. **90**, 404-413).

After plotting the threshold contrast versus this estimated velocity the curves are shifted both horizontally and vertically to fit the curve for $f_s = 1$ c/d. The results are given in Fig. 4.

The horizontal and vertical shifts necessary to obtain the excellent fit are given as dots in Fig. 2 and Fig. 3 respectively.

For the higher velocities the horizontal shifts no longer fit a curve with slope of - 1 (see Fig. 2). This probably is due to the to and fro movement of the grating. Especially for velocities larger than 30 degrees/second the temporal oscillating frequency of the target movement becomes the limiting factor for the pursuit capacity of the eye.

Conclusion

The shape of the Fig. 4 curve very well resembles that of Fig. 1. An exact fit can be found with the curve in Fig. 1 when the Fig. 4 curve is shifted a factor 4 to the right. This suggests that more retinal slip has to be assumed when the eye pursues the grating in our situation than expected from the literature.

The threshold contrast in **Conditions II** and **III** seem to be influenced by the same mechanism. Relating the threshold contrast with the retinal image velocity, (either due to pure target movement, or to slip during pursuit) seems to yield one single curve for the effect of the retinal velocity of the image of a grating on its detectability.

DYNAMIC OVERSHOOT AND POST-SACCADIC DRIFT

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1 INTRODUCTION

Saccadic dynamic overshoot occurs when a primary saccade is followed with *no delay* by a smaller *rapid* movement in the opposite direction (Bahill, Clark & Stark, 1975). On the basis of the velocity and amplitude of these movements, these authors judged them to be saccades. They further reported that in normal subjects 70% of horizontal saccades had dynamic overshoot and that its average size was 0.5 deg.

Because dynamic overshoot delays the moment the eye comes to rest after a saccade, it seems to be useless. Therefore, we wondered if the previously reported high frequency of dynamic overshoot might be an artifact of the photo-electric method used.

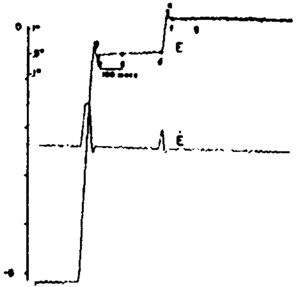
This study re-examines dynamic overshoot by using the magnetic-field/search-coil method. Using an eye coil in each eye simultaneously we have found that dynamic overshoot is a *monocular saccade* ; it occurs frequently and it is associated with least post-saccadic drift.

2 METHODS

Horizontal eye movements were recorded by a magnetic-field/search-coil device (Robinson 1963; Collewijn, van der Mark & Jansen, 1975). The bandwidth was 0-300 Hz for recording eye position and 0-64 Hz for recording eye velocity. System noise level was 0.05 deg. The electro-oculogram was used to monitor blinks.

Six normal subjects took part in the experiment. Five were run in monocular experiments in blocks of 160 trials. To examine the binocularity of dynamic overshoot, three subjects with frequent dynamic overshoot performed, on a different day, a block of 160 trials with an eye coil in each eye simultaneously.

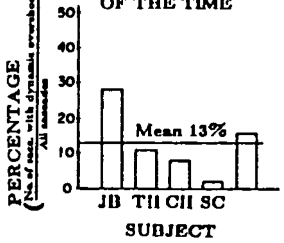
3 TYPICAL EYE-MOVEMENT RECORDING



Eye position (E) and velocity (Ė) for a 5 deg rightward centripetal saccade.

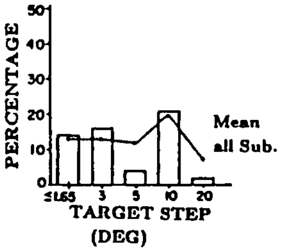
a-b: beginning and end of dynamic overshoot.
b-c: post-saccadic drift
d-e: corrective saccade
e-f: dynamic overshoot
f-g: normal drift

4 DYNAMIC OVERSHOOT OCCURS ABOUT 13% OF THE TIME

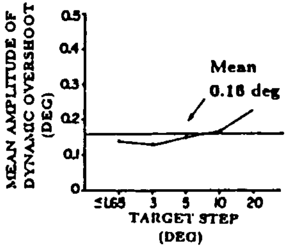


5 FREQUENCY OF DYNAMIC OVERSHOOT IS HIGHER FOR SMALL SACCADES

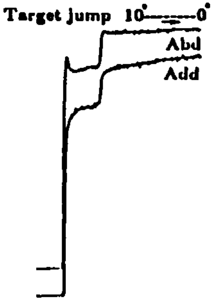
Typical Subject



6 AMPLITUDE OF DYNAMIC OVERSHOOT INCREASES SLIGHTLY WITH SACCADE SIZE



7 TYPICAL BINOCULAR RECORDING

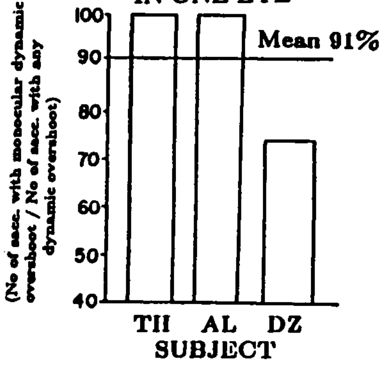


Main findings:

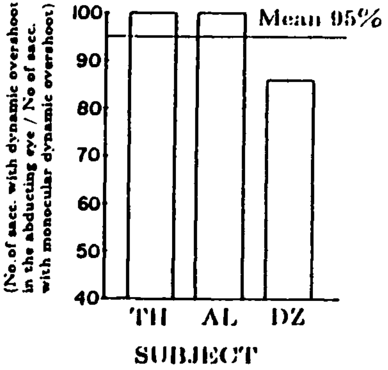
Dynamic overshoot occurs in the abducting eye.

Post-saccadic drift is least in the abducting eye.

8 MOST OF THE DYNAMIC OVERSHOOT OCCURS IN ONE EYE

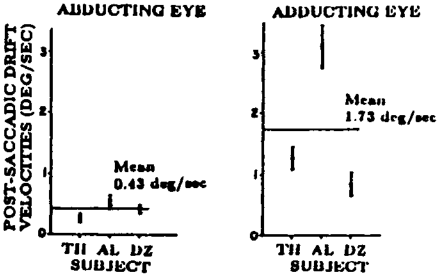


9 DYNAMIC OVERSHOOT OCCURS MAINLY IN THE ABDUCTING EYE



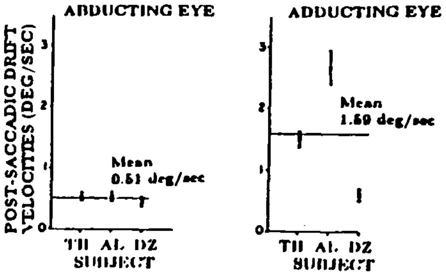
10 POST-SACCADIC DRIFT VELOCITIES ARE SMALLER IN THE ABDUCTING EYE

(THESE ARE SACCADES WITH DYNAMIC OVERSHOOT)



11 POST-SACCADIC DRIFT IS SMALLER IN THE ABDUCTING EYE WITH OR WITHOUT DYNAMIC OVERSHOOT

(THESE SACCADES ARE WITHOUT DYNAMIC OVERSHOOT)



12 CONCLUSIONS

1) Dynamic overshoot is a mistake: we propose that, at the end of a saccade, the eye normally is brought to rest by a braking pulse. If the braking pulse becomes too big, a reverse saccade occurs: dynamic overshoot.

2) Post-saccadic drift in the abducting eye is 3 times less than in the adducting eye. The abducting eye is selected (reason unknown) for best post-saccadic vision .

3) Dynamic overshoot when it occurs is almost always seen in the abducting eye but not in the adducting eye. Dynamic overshoot and post-saccadic drift covary but the former does not cause the latter.

4) Why dynamic overshoot is monocular is a mystery.

REFERENCE

Bahill, A.T., Clark, M.R., & Stark, L. Dynamic overshoot in saccadic eye movements is caused by neurological control signal reversals. *Experimental Neurology*, 1975, *48*, 107-122.

PATTERNS OF INNERVATION IN INTERNUCLEAR OPHTHALMOPLEGIA (INO)

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INTRODUCTION

A generally accepted hypothesis is that in internuclear ophtalmoplegia (INO) the pulse-step mismatch of the oculomotor commands results from a lesion of the medial longitudinal fasciculus (MLF) (see Figure 1). Reconstructed and expected innervation patterns have been compared in order to test several hypothesized effects on the nerve conduction of the MLF-fibers, namely

- loss of nerve fibers
- saturation of high firing rates
- desynchronisation of the different spike trains

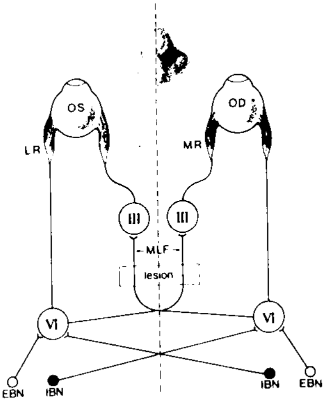

Figure 1: Diagram of anatomic pathways in the brainstem important in the synthesis of horizontal eye movements. EBN = exciting burst neurons; IBN = inhibiting burst neurons; MLF = medial longitudinal fasciculus; LR = lateral rectus; MR = medial rectus; OD = right eye; OS = left eye; III = oculmotor nucleus; IV = abducens nucleus.

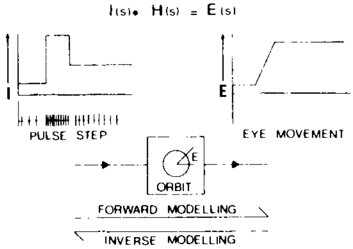

Figure 2: At the left the neural pulse-step signal (I) for a saccade. at the right the produced eye movement (E) are shown; the abscissa scale represents time. The formula describes the process in the Laplace domain.

METHODS

Horizontal and vertical eye movements were measured with the double magnetic induction method (DMI) with a resolution of 5'. Eye position signals were digitized with a sample frequency of 500 Hz, low-pass filtered (150 Hz) and stored in the computer. Fourier deconvolution was used to reconstruct the neural control signal. With this inverse method more realistic pulse-step signals were obtained. The oculomotor plant was approximated by a second order linear low-pass system with the following Laplace transform:

$$H(s) = \frac{k}{(st_1+1)(st_2+1)} \qquad t_1 = 150 \text{ ms} \quad t_2 = 12 \text{ ms} \quad k = 4 \text{ spikes.s}^{-1}.\text{deg}^{-1}$$

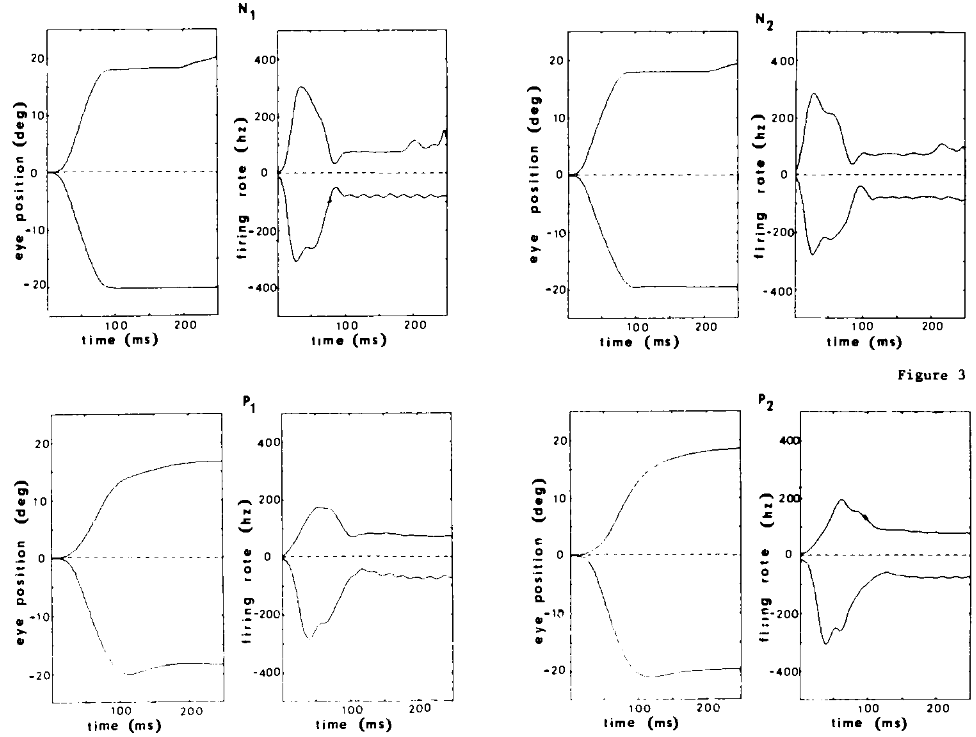

Figure 3

RESULTS

Figure 3 shows the eye movement response of the left eye to a horizontal target jump from 10°left to 10° right of primary position for two normal subjects (N_1, N_2) and two patients (P_1,P_2) with a symmetrical bilateral INO. Also the recontructed net pulse-step innervation (firing rate) is shown. Note that for both patients the maximum of the pulse in adduction does not coincide with the maximum during abduction.

The curve S_1 of Figure 4 shows the actual adducting eye movement of the left eye of patient P_1 and curve S_2 represents a low-pass filtered version (time constant =50 ms) of the abducting eye movement of the same eye. The actual abducting eye movement is shown in curve S_3. With respect to S_1,S_2 has a 'delay' of about 25 ms, which demonstrates that a lesion of the MLF cannot be simply modelled by a low-pass first order filter.

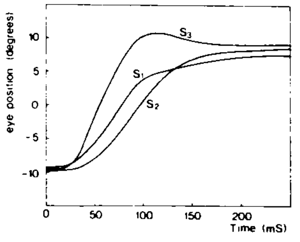

Figure 4

CONCLUSIONS

- In INO the duration of the net pulse innervation of the oculomotor plant seems not to be significantly prolonged, and only the height of the pulse is seriously affected in comparison with normals.
- In a first approximation the lesion of the MLF in INO cannot be simply modelled by a first order low-pass filter.
- Saturation of the net pul innervation in INO cannot be understood merely by static non-linearity.

EYE-HAND-COORDINATION: A REACTION TIME STUDY IN MAN AND MONKEY

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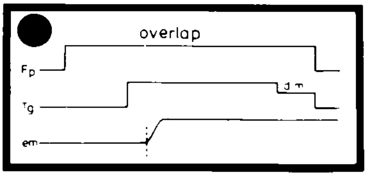
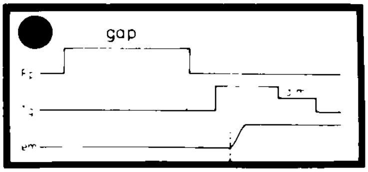
PROBLEM

What the monkey's eye tells the monkey's hand. In a coordinated goal directed eye and hand movement to a single target both movements are prepared under physically identical conditions. The relation between their reaction times reflects the interaction between the processes that precede the movements. Reach reaction times preceded by extremely short latency (80 ms) saccades were compared to those preceded by rather long latency (250 ms) saccades.

A METHODS





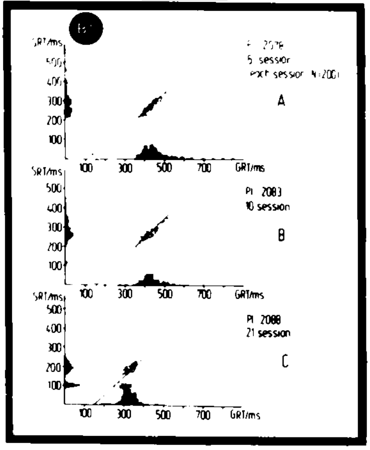
Monkeys were trained to fixate and touch a central fixation point and to saccade and point to a peripheral target (10° eccentric) when it occurred. Reaction times of the eye and the hand were measured and correlated. Two tasks were used. In the "Overlap" task the fixation point remained visible (A1), in the "gap" task (A2) the fixation point went off before the target occurred.

B RESULTS

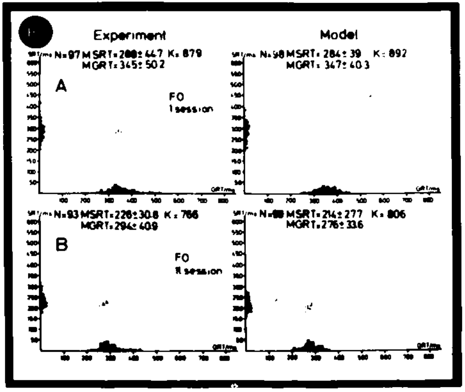
In the overlap task long latency saccades with large scatter were followed by correspondingly long latency reach movements (B1A,B2A). With increasing amounts of practice all reaction times became shorter and the correlation between them was reduced (B1C,B2B). In addition, express saccades occur forming a different set of data in the correlogram (B1C).

SRT Saccadic Reaction Time
GRT Reach Reaction Time

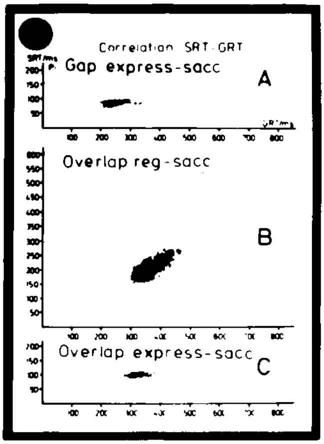
Monkey



Man

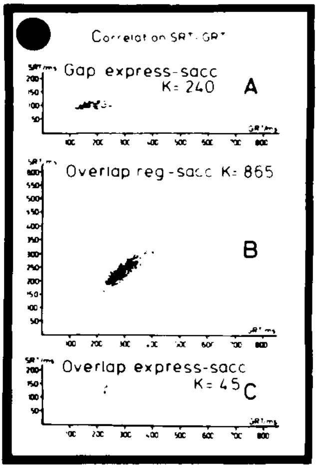


Monkey

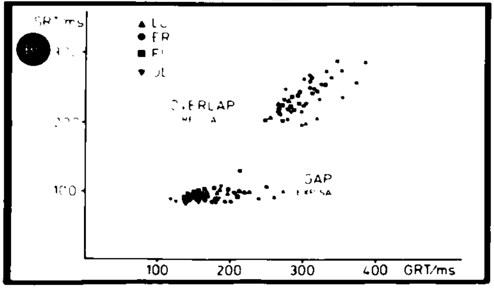


In the gap task many express saccades occur (B3A,B4A), which were followed by correspondingly short latency reach movements and there is no correlation between them. Reach reaction times after express saccades in the overlap task (B3C) are different from those after express saccades in the gap task (B3A).

Man



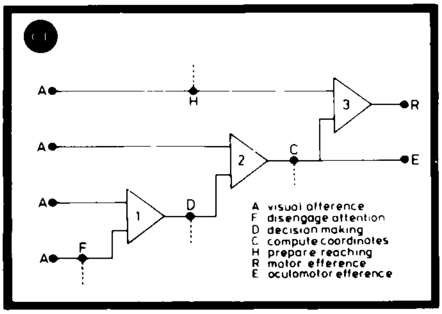
Man



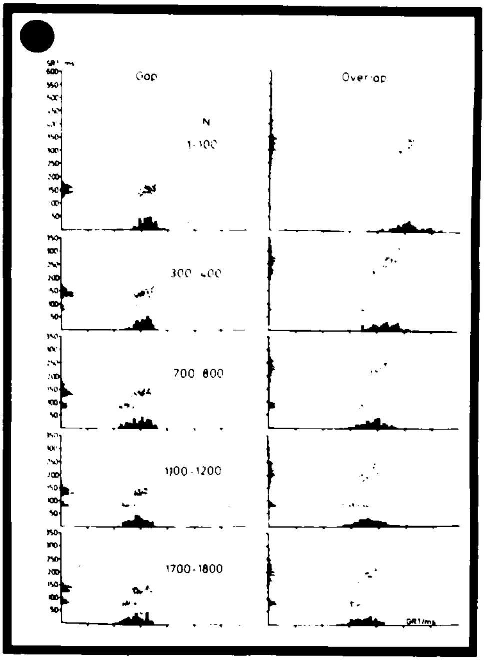
The mean values from different subjects and from different sessions show the same segregation of data points (B5).

C DISCUSSION

A model utilizing logical AND-gates (C1) explains not only the existence of slow regular and express saccades, but also predicts the difference in correlations (B2 right panel). Mainly: for the initiation of the reach movement the preparation of the eye movement must be completed, but not vice versa. A complete set of computed data is shown in C2.



A visual afference
F disengage attention
D decision making
C compute coordinates
H prepare reaching
R motor efference
E oculomotor efference

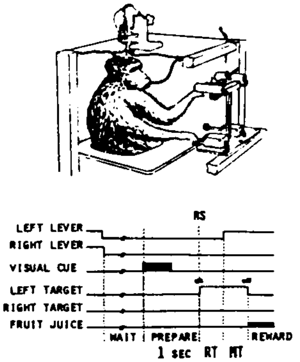


GAZE STRATEGIES OF MONKEYS PERFORMING A OR UNPREDICTABLE TARGETS

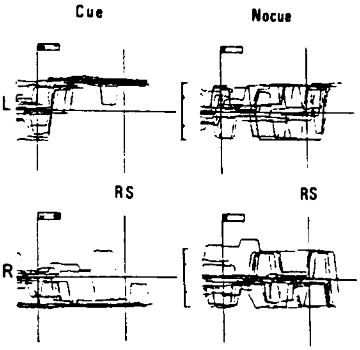
J.C. LECAS[1] AND N. VITTON.

TWO MONKEYS WERE TRAINED ON A BIMANUAL RT-POINTING TASK, WITH OR WITHOUT VISUAL CUEING OF THE TARGET AT THE BEGINNING OF THE PREPARATORY PERIOD.

HORIZONTAL DC-EOG*s*, RECORDED WITH THE HEAD FIXED, WERE PROCESSED TO ASSESS GAZE STRATEGIES ASSOCIATED WITH THE ANTICIPATION OF THE RESPONSE SIGNAL AND THE RELATIONSHIPS BETWEEN EYE-RT AND HAND-RT.



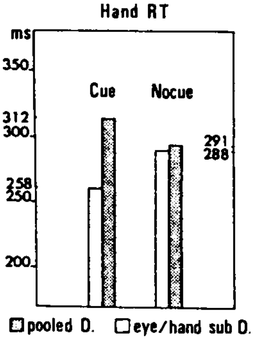
EXPERIMENTAL SET-UP AND TIMING OF A TRIAL. CUES WERE DELIVERED WITH THE CENTRAL L.E.D.✓



SUPERPOSITION OF EOG TRACINGS FOR THE 4 TYPES OF TRIALS. LEVER RELEASE (HAND RT) INDICATED BY THE END OF EOG TRACING. POSITION OF TARGETS AND CUES INDICATED ON CALIBRATION BAR (42°). RS IS RESPONSE SIGNAL. NOTE THE ANTICIPATORY FIXATION OF THE TARGET IN THE CUED TRIALS.

RESULTS.

1. AS EXPECTED, RT WAS 30 *ms* FASTER IN THE CUED TRIALS THAN WHEN THE TARGET WAS UNPREDICTABLE.
2. IN THIS CASE (NOCUE), A CONSISTENT CORRELATION WAS FOUND BETWEEN EYE AND HAND RT*s*, AS PREVIOUSLY SHOWN IN MAN (1).
3. IN THE CUED TRIALS, WHEN FIXATION WAS BROKEN BEFORE RESPONDING, HAND RT COULD BE CORRELATED WITH THE SACCADIC LATENCY TO THE RESPONSE SIGNAL, BUT THEN POINTING WAS 54 *ms* SLOWER THAN THE NOCUE MEAN. IT WAS EVEN SLOWER (24 *ms*) THAN IN THE NOCUE CONDITION.



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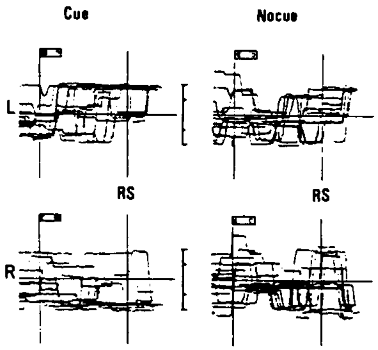
(1) BIGUER B., JEANNEROD M. AND PRABLANC C., EXPERIMENTAL BRAIN RESEARCH, 1982, 46, 301-304.
FISK J.D. AND GOODALE M.A., EXPERIMENTAL BRAIN RESEARCH, 1985, 60, 159-178.

CHOICE REACTION TIME TASK WITH PREDICTABLE FOR ARM MOVEMENTS.

CNRS-INP3, MARSEILLE FRANCE [1] LPN2-CNRS, 91190 GIF-SUR-YVETTE FRANCE

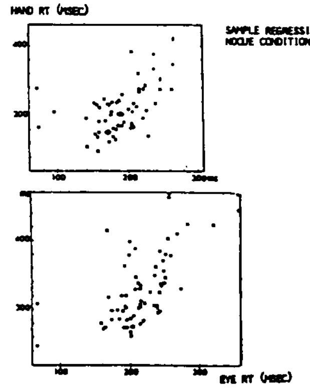


SAME, BUT FOR A LESS WELL TRAINED MONKEY. IN THIS TYPE OF SESSION CORRELATION BETWEEN EYE AND HAND RTs COULD BE COMPUTED EVEN FOR THE CUED TRIALS.

	Cue						Nocue					
	.6	.6	.5	.6	.4	.2	.4	.4	.3	.2	.1	.2
	3.0	6.2	15.5	17.0	18.1	20.9	3.3	2.6	1.9	2.7	3.4	11.8
	4.4	4.4	2.9	2.4	2.0	1.7	3.9	3.5	2.6	2.5	2.1	2.8
L	7.4	5.8	2.9	2.7	2.0	1.2	8.1	9.4	11.0	9.3	10.0	6.9
	6.1	4.8	2.0	1.3	1.0	.6	6.1	6.0	5.8	4.9	3.8	2.8
	3.9	2.8	1.6	1.3	.9	.4	3.6	2.7	3.7	5.9	5.0	3.0
	.1	.0	.0	.0	.0	.0	.1	.0	.0	.1	.2	.0

					RS						RS	
	.7	.5	.4	.2	.1	.1	.5	.5	.4	.3	.1	.1
	3.2	2.5	1.8	2.4	2.1	1.1	3.4	2.9	2.0	2.7	3.2	3.1
	3.9	3.2	2.0	1.7	1.2	.7	4.0	3.3	2.8	2.2	2.4	1.8
R	7.4	5.6	3.1	3.0	2.1	1.1	7.4	9.7	11.3	8.9	10.4	7.2
	6.0	5.5	4.0	2.6	1.8	1.7	5.8	5.5	5.4	4.4	3.8	4.0
	4.1	7.1	13.9	15.3	16.8	17.3	4.2	2.5	3.6	6.8	4.5	9.5
	.1	.2	.3	.3	.4	.4	.2	.1	.1	.2	.1	.2

FIXATION DURATION HISTOGRAMS, AS PERCENTAGES OF THE TRIAL DURATION, DATA POOLED FROM THE TWO MONKEYS AND FROM 10 RECORDING SESSIONS.



SAMPLE REGRESSION SCATTERGRAMS FOR THE NOCUE CONDITION, BETWEEN EYE AND ARM RTs.

	Cue	Nocue
correlations	62.5	100
n.s	22.5	5
s	40	95

CORRELATION BETWEEN EYE AND ARM RT (% OF THE NUMBER OF SESSIONS n= 40)

CONCLUSION : THE EYE AND ARM MOVEMENTS ARE FUNCTIONALLY COUPLED WHEN THE TARGET IS UNPREDICTABLE, WHILE THEY ARE DISSOCIATED WHEN IT CAN BE ANTICIPATED FROM THE CUE. IN THIS CASE, GAZE SHIFTS REFLECT ATTENTION CHANGES, SINCE BREAKING THE FIXATION OF THE TARGET RESULTS IN LENGTHENED RT PERFORMANCE DURING POINTING.

EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

ADAPTATION IN THE OCULOMOTOR SYSTEM

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Adaptive modification in oculomotor behavior is observed in many ecological as well as artifical conditions and the study of its mechanisms has become a major field of research.

It now appears that there are a number of different processes which contribute to adaptation. One of them is a physiological mechanism which consists in a modification of the gain and phase of sensory motor loops. It is similar to parameter adjustments occurring in servo-controlled systems and is often modelled using the theoretical framework of linear systems theory. The oculomotor system is remarkably suited for such description because it is organized in functionally identifiable subsystems. These subsystems have either a stabilizing or an orienting role, they have been divided rather arbitrarily into reflexes, such as the vestibulo-ocular reflex, the optokinetic reflex, the cervico-ocular reflex, etc. and into "systems" such as the pursuit system, the saccadic system, the accommodative vergence system. Each of these subsystems is made of interacting but specific neural circuits in which the adaptation process can be studied.

The general analogy between servo-controlled systems and oculomotor networks has led neurophysiologists and psychologists to concentrate on modifications occurring within each subsystem and to search for detailed neuronal transformations which could explain a whole behavior by plasticity at the level of a few synapses.

Although this approach has been very useful I would like to emphasize an alternative approach which insists upon other mechanisms of adaptation. When faced with an adaptative demand from the environment or from internal disorder due to diseases or lesions the brain probably first tries to meet the demand with modification capabilities which are within the normal physiological range of each subsystem (for instance modification of the gain of the VOR or the amplitude of the saccadic pulse). However, when this is not enough or if one subsystem is defective, or if there is a conflict between several sensory cues, instead of modifying each subsystem, the desired performance is achieved by combining the effect of several subsystems or by suppressing one and substituting another. For instance the saccadic system may be used to provide accurate compensatory eye movements when the VOR is inoperative or non functional during prism adaptation (see review in Berthoz 1985).

These operations of combination or orchestration of subsystems probably play a major role in adaptive mechanisms. This role has not been explored so far. The problem is that they involve mechanisms which cannot be represented by linear systems theory. The cognitive mechanisms implicated should, however, be formalized somehow by a theory which will take into consideration a) the discontinuous and predictive aspect of these operations b) the fact that they have to be organized prior to and during the movement and therefore played without execution c) the global aspect of the control which takes into consideration the context (by contrast with servo-controlled mechanisms which control local parameters). A preliminary proposal has been made of a "dual mode theory" (Droulez et al. 1984, Droulez and Berthoz 1986) which may serve as a basis for discussion of new concepts in the study of adaptation.

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EYE MOVEMENTS: From Physiology to Cognition
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CORTICO-NUCLEAR CIRCUITRY CONTROLLING LATERAL VISUALLY GUIDED SACCADES IN MAN

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France

The cerebral pathways involved in lateral visually guided saccades are reviewed in the light of data from 23 clinical cases with focal cerebral lesions. Lateral saccades are produced in the lower brainstem and both the abducens nucleus and the paramedian pontine reticular formation (PPRF), the final common pathway of all ipsilateral eye movements and of all ipsilateral saccades respectively, are necessary to their existence, as illustrated by the first two cases. Visually guided saccades are triggered by the cerebral cortex and the study of their latencies in 21 cases of focal cerebral hemispheric lesions suggests that three main cortical activities - excitatory parietal, inhibitory frontal and excitatory frontal - play a role in this triggering.

INTRODUCTION

Numerous cerebral structures and pathways are involved in visually guided saccades, but are still imperfectly defined and not all shown in Figure 1. In order to know this organization better, visually guided saccades were studied in 23 clinical cases with unilateral focal cerebral lesions. The mechanisms responsible for final execution of a saccade will be first briefly reviewed apropos 2 cases in which lesions had damaged small parts of the lower brainstem. The cortical areas participating in the triggering of visually guided saccades will then be discussed in the light of both recent experimental data and preliminary results from 21 clinical cases with limited hemispheric lesions.

BRAINSTEM MECHANISMS

The physiological activities developing in the pontine tegmentum during saccades have been recently reviewed (Fuchs, Kaneko and Scudder (1985); Pierrot-Deseilligny (1985)). They are illustrated here by two very different clinical cases in which the abducens nucleus (VI), the final common pathway of all ipsilateral eye movements, and the paramedian pontine reticular formation (PPRF), the immediate premotor relay producing all ipsilateral saccades, had been selectively damaged.

Case 1. In this case, recently reported (Pierrot-Deseilligny and Goasguen (1984)), the patient had a complete paralysis of all rightward eye movements associated with a right peripheral facial paresis only (Figure 2 Aa1). By contrast, most eye movements were preserved in the left hemifield of movement. In particular, leftward saccades were normal and return saccades (directed rightwards, between the left lateral position and the midline) were also present, although slightly slower (Fig. 2 Aa2). The lesion (histiocytosis X), clearly visible on CT scan, lay essentially in the fourth ventricle with a small anterior extension in the right posterior paramedian part of the pontine tegmentum (Fig. 2Ab).

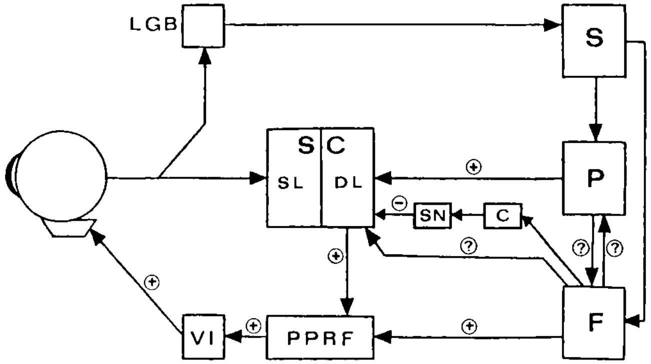

Figure 1. Pathways involved in visually guided saccades.

C = caudate nucleus; DL = deep layers; F = frontal eye fields; LGB = lateral geniculate body; P = inferior parietal lobule; PPRF = paramedian pontine reticular formation; S = striate cortex; SC = superior colliculus; SL = superficial layers; SN = substantia nigra; VI = abducens nucleus.

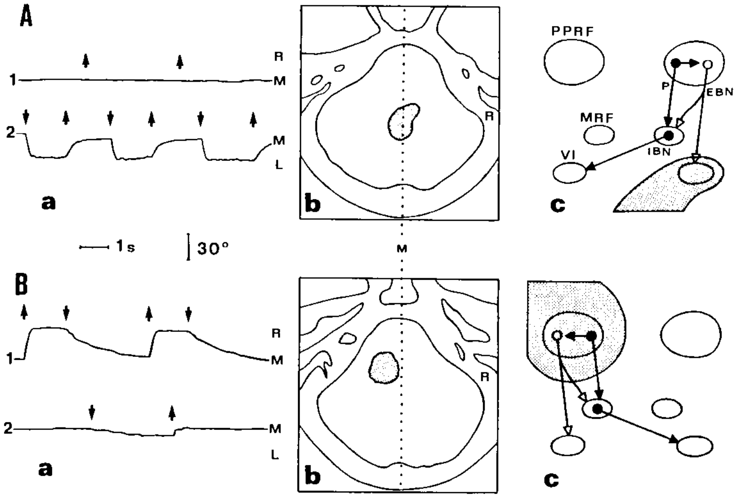

Figure 2. Paralyses of saccades pontine in origin.

A) Abducens nucleus syndrome; a) EOG recording of saccades (left eye); 1) rightward saccades (upward arrows) : no movement; 2) leftward saccades (downward arrows), normal, with return saccades (upward arrows) present but slightly slow; b) drawing of CT scan (see text); c) physiological interpretation.
B) PPRF syndrome; a) EOG recording of saccades (right eye); 1) rightward saccades (upward arrows)), normal but extremely slow return to the midline (downward arrows); 2) leftward saccade (downward arrows) : very slow movement of few degrees only; b) drawing of CT scan (see text); c) physiopathological interpretation.
EBN = excitatory burst neuron; IBN = inhibitory burst neuron; L = left; M = midline; MRF = medullary reticular formation; P = pause neuron; PPRF = paramedian pontine reticular formation; R = right; VI = abducens nucleus.

Comments. These clinical and topographical features suggest that the right abducens nucleus had been selectively damaged by the lesion (Fig. 2Ac). The presence of rightward saccades in the left hemifield of movement is explained by the fact that the inhibitory burst neurons, more anteriorly located than the abducens nucleus in the pontine tegmentum (Porter, Guthrie and Sparks (1985)), had probably been spared. The inhibitory burst neurons which phasically inhibit the contralateral abducens nucleus during all ipsilateral saccades (Hikosaka and Kawakami (1977); Yoshida, McCrea, Berthoz and Vidal (1982)), would be controlled both by the pause neurons and the excitatory burst neurons of the ipsilateral paramedian pontine reticular formation (PPRF) (Yoshida et al. (1982)),located anteriorly and rostrally to the abducens nucleus (Fuchs et al. (1985)) and consequently undamaged in this case. Thus, all the structures necessary to inhibit the antagonist muscles phasically during rightward saccades were preserved, which explains why these movements still existed between the left and the midline, their slight slowness being due to the absence of the concomitant excitation of the agonist muscles.

Case 2. A 74-year-old man had an oculomotor syndrome and a partial sensitivity deficit on the whole left side of the body, occurring suddenly and simultaneously two months previously. Rightward saccades were normal but, in contrast to the previous case, return saccades to the midline (directed leftwards) were absent, being replaced by a very slow movement, with a velocity of 10°/s (Fig. 2 Ba1). Attempts at leftward saccades beyond the midline resulted in a very slow movement, with an amplitude of a few degrees only (Fig. 2Ba2). With passive cephalic movements (not shown) the right eye was able to reach the left extreme lateral position, but the left eye was only able to move in the right hemifield of movement (with, therefore, a total abductive paralysis of this eye). The lesion visible on CT scan was located on the left side and was much more anterior in the pontine tegmentum than in Case 1 (Fig. 2Bb).

Comments. These clinical and topographical features suggest that the lesion had damaged both the left PPRF (Fig. 2Bc) and the radicular fibers of the left abducens nucleus (passing through the lower extremity of the PPRF). The left abducens nucleus itself was spared since vestibular eye movements persisted in the left hemifield of movement of the right eye : for detailed discussion see previous reports of the same syndrome (Pierrot-Deseilligny et al. (1979, 1982)). As both the left excitatory burst neurons and inhibitory burst neurons were impaired (the latter being either damaged ventrally to the abducens nucleus or simply disconnected from the PPRF), no leftward saccades could persist, including those which should have occured in the right hemifield of movement.

CORTICAL MECHANISMS

The suprareticular mechanisms leading to the triggering of visually guided saccades have lately been better understood (see for review Zee (1984)). In particular, it is now clear in the monkey that both the frontal eye fields and the deep layers of the superior colliculus are involved. It has been shown that the frontal eye fields (see for review Bruce and Goldberg (1985)) and the superior colliculus (see for review Wurtz and Albano (1980)) contain cells involved just before visually guided saccades and that stimulation of either structure induces contralateral saccadic eye movement (Schiller, True and Conway (1979)). The frontal eye fields (Leichnetz, Smith and Spencer (1984)) and the superior colliculus (Harting (1977)) project directly onto the PPRF, with predominantly contralateral projections, and bilateral lesions of either structure induce only subtle and transient oculomotor deficits, while bilateral lesions of both induce a severe and long-lasting impairment of saccades (Schiller, True and Conway (1980)). In fact, the deep layers of the superior colliculus could only be a relay in an excitatory pathway originating from the inferior parietal lobule, and more precisely from the lateral bank of the posterior part of the intraparietal sulcus, the supero-anterior border of area 7 of the monkey and of area 39 (the angular gyrus) of man (Pierrot-Deseilligny (1985)) : 1) in monkey, this cortical area contains neurons involved just before the onset of visually guided saccades (Lynch, Mountcastle, Talbot and Yin (1977)); 2) stimulations of this area induce saccades in the monkey (Shibunati, Sakata and Hyvarïnen (1984)), which are not observed if the superior colliculus has been previously destroyed (Keating, Gooley, Pratt and Kelsey (1983)); 3) this area directly projects onto the deep layers of the superior colliculus in the monkey (Fries (1984); Lynch, Graybiel and Lobeck (1985)); 4) in man, bilateral damage to the supero-anterior extremity of the angular gyrus and to the adjacent intraparietal sulcus - which corresponds exactly to the parietal area involved in visually guided saccades in the monkey - has induced a selective impairment of visually guided saccades, whose latencies were largely increased and whose accuracy (direction as well as amplitude) was extremely defective (Pierrot-Deseilligny, Gray and Brunet (1986)). Consequently, it now appears probable that the two main parallel excitatory pathways involved in the triggering of visually guided saccades are (Fig. 1) : 1) the fronto-reticular pathway, originating from the frontal eye fields and projecting directly onto the premotor reticular formations of the brainstem; and 2) the parieto-reticular pathway, originating from the inferior parietal lobule and projecting onto the same structures via a relay in the superior colliculus. Furthermore, a third pathway, mediating a tonic inhibition (stopping just prior to visually guided saccades) and connecting the frontal eye fields with the superior colliculus via relays in the body of the caudate nucleus and the substantia nigra (Hikosaka and Wurtz (1983, 1985)), could also participate in this triggering.

Material and methods. The specific functional influence of the frontal eye fields and inferior parietal lobule in the triggering of visually guided saccades was studied by measuring saccade latency in 21 patients with recent hemispheric cerebral lesions and without hemianopia. The lesions were located in both cerebral hemispheres, but they had to be unilateral, unique, well limited on CT scan and either entirely anterior (Table 1) or entirely posterior (Table 2) to the central sulcus to be included. Moreover, in the frontal lobe, the lesions had to involve the frontal eye fields (located at the posterior extremity of the second frontal gyrus) and/or the underlying white matter, while in the parietal lobe the lesions had to involve the cortex of the posterior part of the inferior parietal lobule and/or the underlying white matter. The mean age of these 21 patients was 59 years (SD = 14 years) and the other clinical characteristics are summarized in Tables 1 and 2. Visual neglect was tested according to the method proposed by Chain, Leblanc, Chédru and Lhermitte (1979).

Lateral saccades were recorded in darkness by electro-oculography with immobilization of the head. The subject was required to fixate a central luminous point which disappeared on average 100 ms (but in fact between 50 and 150 ms) before the onset of the lateral point (25 degrees from the central point), which then had to be fixated as quickly as possible. The stimulus presentation order was randomized both in time and space, with 20 saccades in each lateral direction. Right and left latencies were measured in the 21 patients and compared with those of a control group of 30 subjects : age = 55 ± 13 years; right latencies = 238 ± 39 ms; left latencies = 239 ± 36 ms.

Results. In the 10 parietal cases (Table 1) latencies were significantly increased bilaterally in 9 cases and only slightly increased in one case (Case 9). As the mean age of these patients was 60 years, namely close to the mean age of the control group, age was not an explanation for the latency increase. The associated visual neglect (tested in 9 cases and present with various intensities in 8 cases), always clearly contralateral to the lesion, could not explain the latency increase, which was bilateral, either. Lastly, this disorder was observed in right lesions (6 cases) as well as in left lesions (4 cases) and appeared relatively long-lasting since the mean age of the 9 vascular lesions of this group was 59 days (SD = 44 days).

Case	Age	Location of lesion	Side of lesion	Nature of lesion	Age of lesion	Visual neglect	Latencies of visually guided saccades (ms)	
							Right	Left
3	46	P	R	Hematoma	30d	1	319 ± 96 **	403 ± 30 **
4	76	P	R	Infarct	37d	3	379 ± 128 **	373 ± 79 **
5	55	P-T	R	Infarct	19d	3	324 ± 109 **	322 ± 138 **
6	67	P	R	Infarct	44d	2	446 ± 144 **	467 ± 161 **
7	40	P	L	Infarct	105d	0	376 ± 91 **	359 ± 60 **
8	83	P	L	Infarct	115d	-	354 ± 53 **	380 ± 124 **
9	44	P-O	R	Infarct	44d	3	300 ± 67	285 ± 27
10	80	P-O	R	Tumour	6w	3	446 ± 111 **	450 ± 128 **
11	49	P-O	L	Hematoma	125d	1	339 ± 54 **	327 ± 70 **
12	60	P-O	L	Infarct	8d	3	413 ± 79 **	422 ± 47 **

Table I.
Frontal cases

c = cortical; d = day; F = frontal; L = left; P = parietal; O = occipital; R = right; sc = subcortical; T = temporal; w = week; 0 = no visual neglect; 1 = mild; 2 = moderate; 3 = severe; - = not tested; * = value significantly decreased; ** = value significantly increased.

Case	Age	Location of lesion	Side of lesion	Nature of lesion	Age of lesion	Visual neglect	Latencies of visually guided saccades (ms)	
							Right	left
13	55	F-c	R	Infarct	30d	2	151 ± 57 *	147 ± 40 *
14	26	F-c	R	Infarct	31d	3	148 ± 39 *	159 ± 12 *
15	56	F-c	L	Infarct	10d	0	183 ± 68	177 ± 54
16	55	F-c-sc	L	Tumour	8w	0	220 ± 41	160 ± 34 *
17	75	F-c-sc	R	Infarct	22d	0	241 ± 74	162 ± 40 *
18	61	F-c-sc	R	Infarct	205d	3	161 ± 43 *	248 ± 56
19	65	F-c-sc	R	Tumour	3w	3	160 ± 33 *	238 ± 21
20	60	F-sc	R	Infarct	45d	3	225 ± 44	324 ± 78 **
21	71	F-sc	R	Infarct	34d	3	192 ± 25	407 ± 86 **
22	58	F-sc	L	Tumour	?	0	358 ± 77 **	257 ± 69
23	66	F-sc	R	Infarct	30d	1	240 ± 40	320 ± 59 **

Table II.
Parietal cases (abbreviations : see Table I)

In the 11 frontal cases, latencies were significantly decreased in 6 cases, bilaterally in 2 cases and unilaterally (ipsilaterally to the lesion)in 4 cases. It must be noted that in Cases 13 and 14, in which latencies were decreased bilaterally, as well as in Case 15, in which latencies were only slightly decreased (but also bilaterally), lesions involved the frontal eye fields but barely extended to the subcortical region, while in the 8 other cases lesions also largely involved the underlying white matter at least up to the region lateral to the body of the corpus callosum. In these 8 cases (Cases 16 to 23) right and left latencies were significantly asymmetrical, contrary to Cases 3 to 15 . This asymmetry, discussed elsewhere (Pierrot-Deseilligny, Rivaud, Penet and Rigolet (1986)), could be due to the impairment of certain efferent fibers of the frontal eye fields decussating through the corpus callosum. Lastly, in the last four cases (Cases 20 to 23) in which lesions were essentially subcortical (close to the corpus callosum), latencies contralateral to the lesion were significantly increased. The mean age of this frontal group was also close to the mean age of the control group, the lesions involved both hemispheres (8 right lesions and 3 left lesions) and, as in the parietal group, visual neglect did not explain the latency anomalies since it was absent in four cases.

Comments. Although these results must be considered as preliminary, the study not being longitudinal and the number of cases being too few (in particular in the frontal region), several trends seem to be emerging. Firstly, unilateral posterior parietal lesions resulted in a bilateral increase of latencies of visually guided saccades, without asymmetry. These results are different from those of a previous study (Sunqvist (1979)) in which latencies of parietal cases were slightly increased and asymmetrical. However, as the lesions in this study were located in "the parietal region", without further anatomical precision, it may be assumed that the asymmetry was due to damage to the immediately adjacent posterior frontal region, through which the different efferent tracts of the frontal eye fields pass and whose impairment is clearly correlated in our study with asymmetrical cases. Finally, our data provide further argument in support of the participation of the parietal lobe in the triggering of visually guided saccades and suggest, furthermore, that this action is essentially a facilitation, since latencies are increased after lesions, and is not lateralized since impairment is bilateral. This action would be mediated at least in part by the direct connection of the inferior parietal lobule to the superior colliculus and possibly in part via the frontal eye fields onto which the inferior parietal lobule also projects (Petrides and Pandya (1984)) (Fig. 1).

Secondly, unilateral posterior frontal lesions resulted, in the majority of cases (7/11), in a decrease of latencies, bilaterally or only ipsilaterally to the lesion depending on whether the damage involved essentially the cortex or also extended largely to the subcortical region up to the corpus callosum. Our results differ from those of a previous study (Guitton, Buchtel and Douglas (1985)) in which, after purely cortical frontal lesions, latencies of visually guided saccades were also significantly decreased bilaterally, but only for a more complicated visuo-oculomotor task than that performed here. Nevertheless, it may be considered that after a lesion of the frontal eye fields, extending or not to the underlying white matter, through which their efferent tracts probably pass, latencies of visually guided saccades have a tendency to be decreased. These findings suggest that each frontal lobe normally exerts some bilateral tonic inhibition onto the triggering of visually guided saccades, perhaps by the inhibitory pathway recently described, connecting the frontal eye fields with the superior colliculus, via several relays - in particular in the substantia nigra (see above) - or without any relays since a direct pathway also exists (Leichnetz, Spencer, Hardy and Astruc (1981)).

Thirdly, in a minority of frontal cases (4/11), in which lesions were essentially subcortical, latencies were not only asymmetrical, but also significantly increased contralaterally to the lesion. These data suggest that the frontal lobe could also exert an excitatory influence on the triggering of visually guided saccades, probably transmitted directly onto the premotor reticular formations (see above). Accordingly, the frontal lobe could either inhibit or facilitate visually guided saccades, depending on the circumstances : in fact, concerning this type of saccades, it would especially preserve foveal visual analysis, by inhibiting the unwanted reflexive visual saccades, while the parietal lobe would preserve the peripheral visual exploration, by facilitating visual saccades. The latency of visually guided saccades would largely reflect the multiple exchanges of messages between these two cortical structures, mutually helping or opposing each other in turn. This could explain the rather large variability of latencies from one saccade to another in the same subject, particulary in those pathological states where certain direct tracts are impaired.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

ADAPTIVITY OF GAIN AND DIRECTION IN OBLIQUE SACCADES[1]

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This study, performed in man and monkey, addresses the question of adaptive control of amplitude and direction of saccadic eye movements with both horizontal and vertical components.

In two different types of experiments, the saccadic responses were adaptively modified by shifting the target during the primary saccade in a direction opposite to the initial target step, or, orthogonally to the initial step. The data reveal that the respectively induced gain and direction changes of the saccadic responses are specific to the direction of the eye movements: the effect of modification is limited to saccades within angles of approx. ±30 deg around the adapted direction.

INTRODUCTION

Most investigations on properties of the eye movement system have been limited to purely horizontal and, to a lesser extent, purely vertical saccades. Only a small number of studies exist on eye movements with both horizontal and vertical components. Accordingly, our knowledge about the interaction of horizontal and vertical subsystems in oblique saccades is rather limited.

We investigated one important property of the saccadic system, its adaptivity, for saccades in both dimensions. The study represents a continuation of work on parametric adjustment of horizontal saccades (Wolf, Deubel and Hauske (1984)). In this former study we found that parametric adjustment of saccadic gain is specific to the direction of the movement. This means that induced gain changes in, for example, leftward saccades, do not transfer to rightward saccades. This finding was related to the fact that the saccadic system is organized in two to some extent independent subsystems for left and right saccades. Another finding was that, keeping target and movement in one hemisphere, adaptivity is not specific to the amplitude of the saccade which means that training of saccades of a certain amplitude transfers to saccades of other sizes. The question arises how these findings manifest themselves for oblique saccades. More specifically, we asked: does adaptation for vertical components exist, and if so, what are their properties?

A further point of interest concerned the organization principles of saccadic adaptation. From single-unit recordings it has been well established that at premotor and motor neuron levels, the saccadic system is organized in a Cartesian coordinate system. At this peripheral level, the paramedian pontine reticular formation and the mesencephalic reticular formation are responsible for the generation of the horizontal and vertical components of saccades, respectively, which form the final saccade vector (Luschei and Fuchs (1972); King and Fuchs (1979)). At the more central level of the superior colliculus and the frontal eye fields, on the other hand, retinotopic maps exist in which retinal error is spatially coded (Wurtz and Albano (1980)). At this stage of visual-motor processing, the organization of the saccadic system can be better described in terms of polar coordinates.

The different organization principles at different levels of the saccadic system noted above should be reflected in properties of saccadic programming associated with these levels. As to saccadic adaptation, in a system where horizontal and vertical components are independently adaptable, different saccadic directions would be affected according to these components. This was tested by investigating the adaptivity of oblique saccades and the amount of transfer to saccades into different directions.

METHODS

In order to allow comparison between the psychophysical data available from former studies in human subjects (McLaughlin (1967); Wolf, Deubel and Hauske (1984)) and the data from neurophysiological studies in monkeys, the experiments were done with both man and monkey.

Subjects were 4 scientists from the laboratory and the author. Eye movements were recorded monocularly in both dimensions with the magnetic field scleral search coil technique introduced by Robinson (1963). Resolution of the eye movement recording was better than 5 min arc. The analogue eye position signal was sampled at 500 Hz, digitized with 12 bit precision and stored on disk for later off-line analysis. The targets consisted in small bright spots of light projected on a large white screen at a viewing distance of 110 cm. Motion of the target spots was controlled by servo-controlled mirror galvanometers with a bandwidth better than 100 Hz.

For the animal studies, adult Rhesus monkeys were used. The monkeys were well-trained to follow and fixate small spots of light in the dark, being rewarded for their performance with drops of water. The rhesus monkeys were implanted with a head holder and a scleral search coil. During the experiments the animals were seated in a plastic chair facing a white screen at a distance of 97 cm.

As with most adaptation paradigms, each session consisted of three phases:

I) A pre-adaptation test phase in which the normal parameters of the saccadic response were obtained. In this phase of the experiments, only single target steps were given.

II) The adaptation phase. In the majority of the experiments reported, in this phase only saccades into the directions under adaptation were elicited.

III) The post-adaptation test phase, where the effects of the adaptive changes were determined.

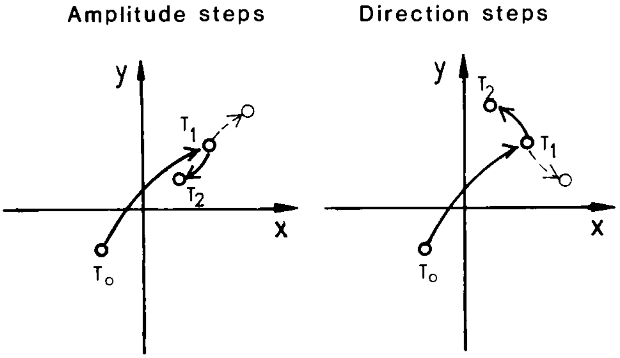


Figure 1

Experimental paradigms. Left: Amplitude step condition. During the saccade, the target is displaced in the opposite (or same) direction as the initial step ($T_1 \rightarrow T_2$). Right: Direction step condition. The intrasaccadic target step occurs orthogonally to the first step.

A single trial was of the following type:
After 500 - 1000 msec of fixation controlled on-line by the computer, the target was displaced by 6 - 12 deg. Direction of the target step was selected at random from a given repertoire of angles. Subjects had to follow the target as fast as possible.

For adaptation, a second, intrasaccadic target displacement was triggered by the primary saccade using a 50 deg/sec criterion. It is well known that small, intrasaccadic targets are not perceived by the subjects (Bridgeman, Hendry and Stark (1975)). The size of the second target step was selected to be a certain percentage (in most cases 30%) of the size of the initial step. Due to the artificially induced refixation errors, large, visually guided corrective saccades were elicited (Deubel, Wolf and Hauske (1982)). The final target position after this sequence of one or two steps served as the starting point for the next trial.

Depending on the direction of the intrasaccadic step, two basic conditions are distinguished (Fig. 1):

I. Amplitude steps: The intrasaccadic target step occurs in the opposite (or same) direction as the first step.

II. Direction steps: The intrasaccadic target displacement occurs orthogonally to the direction of the first target step.

RESULTS

Precision of oblique saccades

In order to give an idea of the normal precision of oblique saccades, data from the pre-adaptation test phase is presented first. Fig. 2 displays radial gain and direction of individual saccades to targets given at angles of multiples of 22.5 deg. Generally, human subjects tend to exhibit large undershoots in saccades with upward direction. Rhesus monkeys yield a somewhat opposite behaviour; their upward saccades generally have gain higher than one.

Another important aspect which is revealed from these data concerns the coding of the response. If the saccade vectors were composed of noisy but independent x and y components, one should expect a circular form of saccadic scatter. The data, however, clearly argue for a polar coordinate system in which programming of direction is less noisy than programming of saccadic amplitude. Generally, standard deviations of radial gain were found to be by a factor of 2 - 3 higher than appropriately normalized standard deviations of directions.

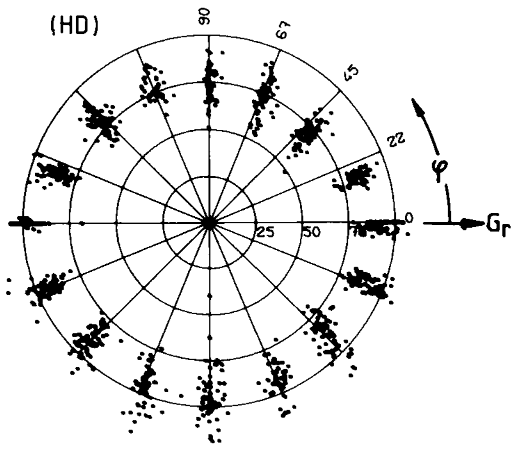


Figure 2
Radial gain G_r in percent of target step size and direction φ of individual saccades to targets presented at angles of multiples of 22.5 deg (Subject HD).

Amplitude steps

Next, some typical examples of responses to consistent amplitude steps are presented. Given modified feedback of this kind we in fact found that saccades in all directions are susceptible to adaptive gain changes.

The left part of Fig. 3 illustrates time courses for the gain decrease condition, determined for a human subject (FM) and different saccadic directions under adaptation. The right diagram shows corresponding monkey data (Monkey L). For human subjects time constants for gain decreases are generally of the order of 30 - 60 trials and are essentially independent of saccadic directions. Gain increases, on the other hand, are considerably slower, yielding time constants of more than 400 trials.

The rhesus monkeys generally adapted by a factor of 10 slower than the tested subjects. Again it is more difficult to establish gain increases than gain decreases.

After having induced sufficient adaptation of one or more directions in the adaptation phase, which took some 100 trials for the human subjects and 1000 - 2000 trials for the monkeys, we investigated how saccades of other directions were affected by the adaptation.

Fig. 4 provides typical examples of the results from human subjects. It is important to note that the picture emerging from the monkey data is practically identical to the human data. The upper left diagram of the figure shows mean radial gain and direction and their standard deviations. Open circles denote data from the unadapted state, filled circles represent the data from the post-adaptation phase. As expected, the largest change is revealed for the movement directions which were previously adapted. Adjacent directions also show reduced saccadic gains. It can be seen, however, that the effect decreases sharply with angular distance from the adapted direction. This becomes more obvious in the other diagrams of the figure, giving the percentage change of radial gain for the different stimulus directions.

Evidently, the effect is tightly tuned; gain can be adjusted independently for saccadic directions with moderate angular distance. Thus, at a distance of 15 deg from the previously adapted angle, the induced gain changes are already reduced by

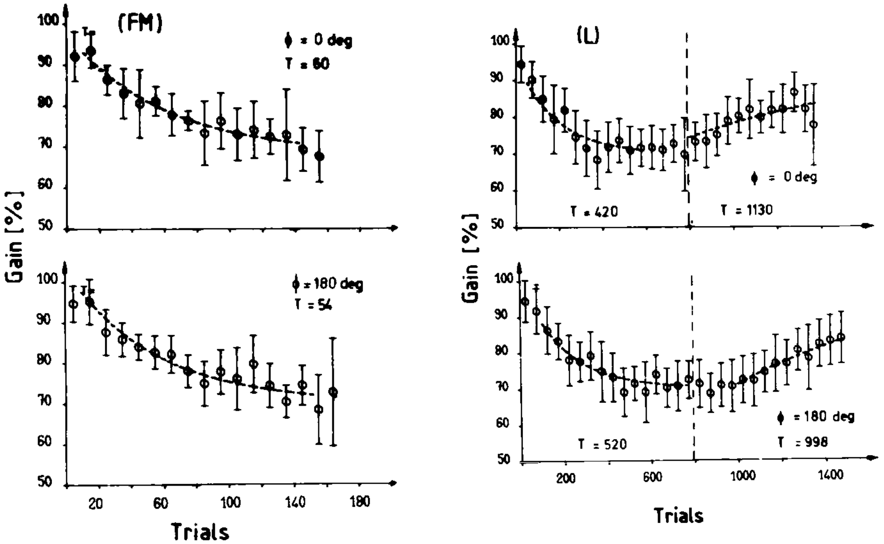


Figure 3
Time courses for radial gain changes, determined for different saccadic directions ϕ. Estimated time constants T are given in the insets of the plots. Left diagram: human subject FM; right diagram: monkey L.

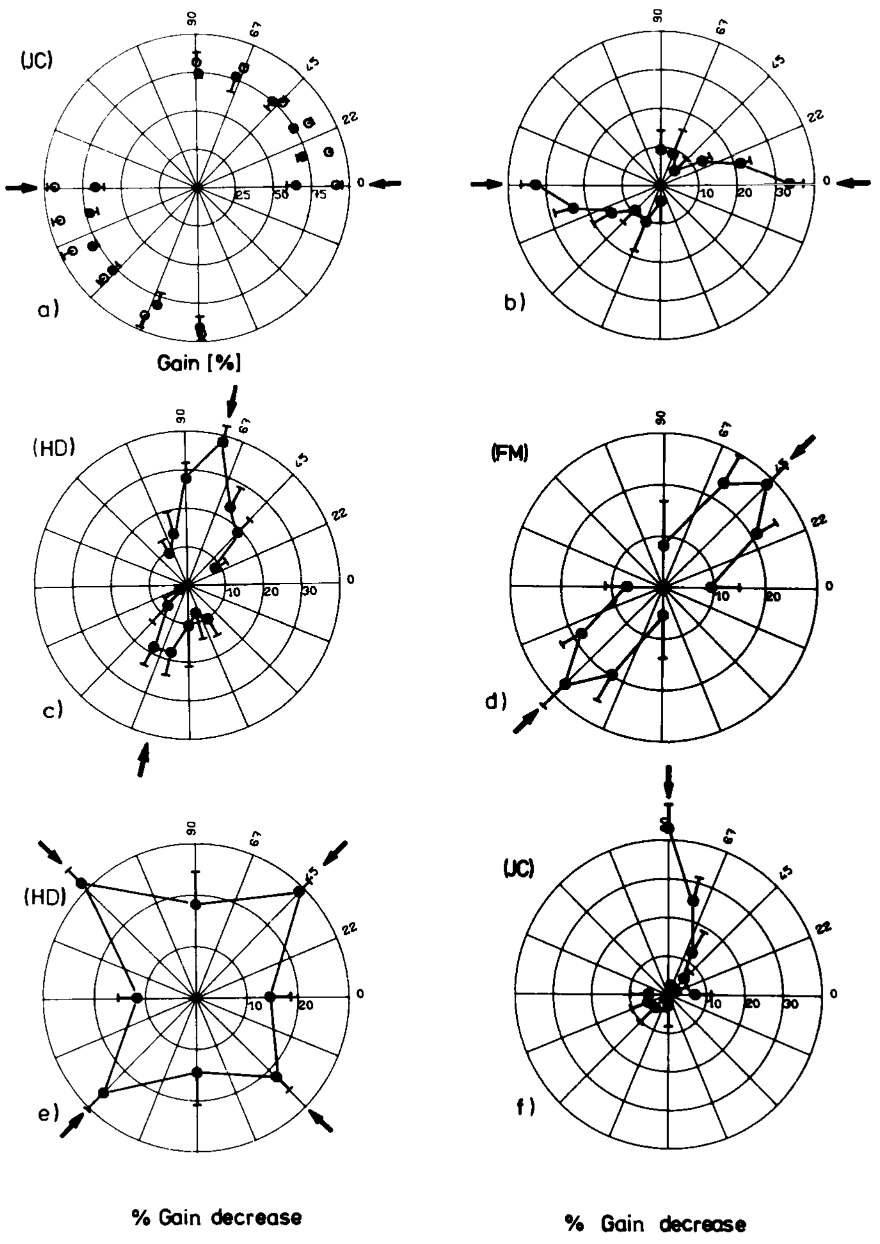


Figure 4
a) Radial saccadic gain and direction (Subject JC). Open circles represent data from the unadapted state; filled circles present the data from the post-adaptation test phase. Arrows denote the target angles which were adapted. Radial and tangent bars represent standard deviations.
b) Percentage changes of radial gain due to the adaptation, given for the tested saccade angles. Radial bars indicate twice the 99.5% significance levels for the difference between pre- and post-adaptation means.
c-f) Same as b), but for different subjects and adapted angles.

a factor of 2, on the average. It can be concluded that a sharp directional selectivity of the parametric adjustment effect exists. Adaptation is clearly more specific than an organization based on independent x and y components would predict. The tuning properties are largely independent of angle and number of directions adapted. So, the figure gives an example of unidirectional adaptation (f) and from an experiment, where 4 directions were adapted (e). The data from the latter case suggests that the effect is additive. Further, the tuning properties are homogeneous in the whole visual field. This can be seen from Fig. 4c where adaptation of saccades with a small leftward component transfers undisturbed to saccades with a small rightward component. It can be concluded that the main axes associated with purely horizontal or vertical saccades do not play a specific role in saccadic adaptation.

Direction steps

The next question we addressed was: is direction itself adaptively modifiable? In these experiments the direction-step paradigm was used (see Fig. 1) in which, for adaptation, the target was displaced orthogonally to the direction of the initial step. Again, given that the intrasaccadic steps are small enough, they are not perceived by the subjects.

The surprising finding was that saccadic direction is in fact equally adaptable as saccadic gain. Fig. 5 shows some time courses from these adaptation phases, on the left side, for two human subjects, on the right for the two rhesus monkeys. Also in this case the time constants for humans are in the range of 30 - 60 trials; the monkeys yield time constants of about 200 trials. It should be mentioned briefly that some anisotropies exist; some directions can not be as easily adapted as others. Again, after adaptation the spread of direction modification to saccades for adjacent angles was tested. The data displayed in Fig. 6 stem from subject FM and monkey L. Pre-adaptive data is shown by the open symbols, post-adaptive data by the filled symbols. Thick arrows give adapted angle and direction of intrasaccadic target displacement. The data again reveal that only directions close to the adapted one are affected. The right plots give an impression of the tuning curve; they show the difference of saccadic direction between pre- and post-adaptation phase.

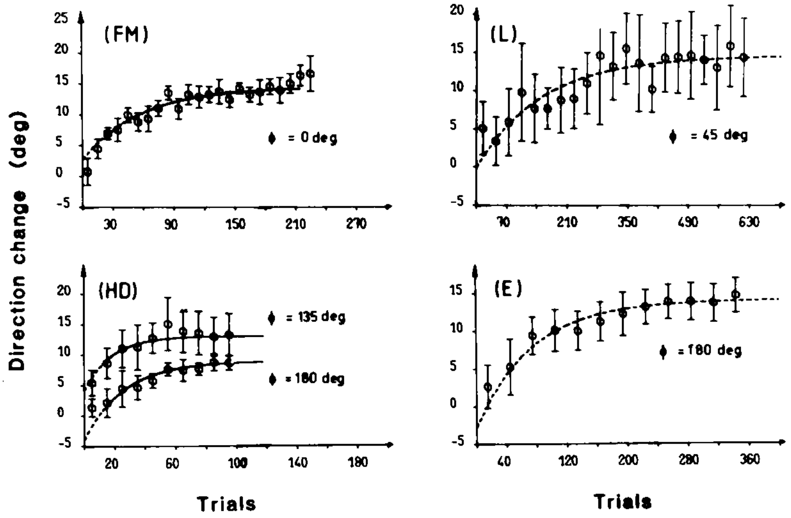
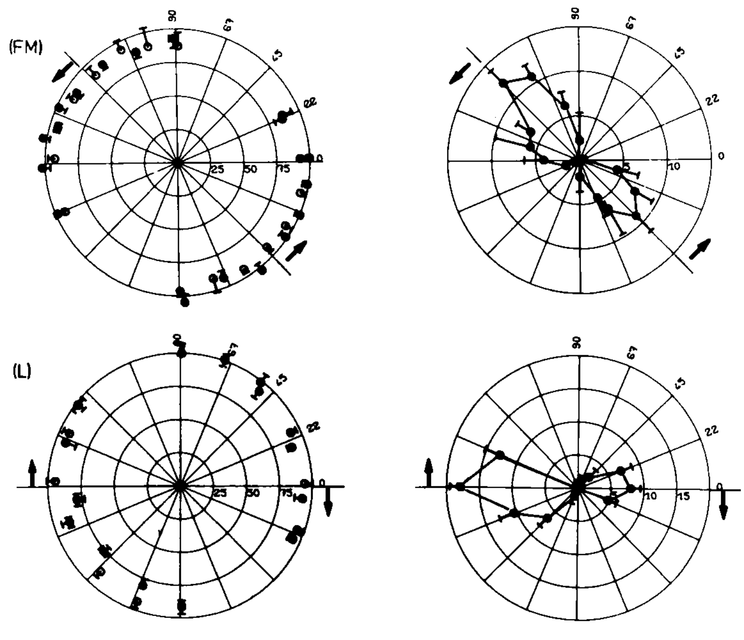


Figure 5
Time courses for adaptive changes of saccadic directions in the "Direction step" experiments. Left diagrams: Subjects FM, HD. Right diagrams: monkeys L, E.

Again, the angular change is highest for the adapted direction, decreasing sharply with angular distance. It is obvious that the tuning width is very similar to the results from the amplitude step experiments. The data from the rhesus monkeys are essentially identical to those from the human subjects. We conclude that saccadic direction can be easily modified in primates and that this type of adaptation is directionally selective.

Coding of the adaptive modification

Generally, the picture emerging from the above data is that magnitude r and angle ϕ are the two coordinates in which saccadic adaptivity is coded. After a close look at the induced changes, however, it becomes evident that these components are not independently adaptable. Thus, Fig. 7 represents some of the previously shown data, this time displaying the induced changes from before to after adaptation as vectors. It can be seen that the direction of the induced changes is maintained for the adjacent angles tested. This means that, adapting radial gain of the specific movement direction, radial gain and angles of other saccadic directions are effected. This finding is especially pronounced in the data from the rhesus monkeys.



Gain [%]

Direction change [deg]

Figure 6
Left diagrams: Mean radial gain and direction of saccades before (open circles) and after (filled circles) adaptation in a Direction Step experiment. Data shown stem from subject FM and monkey L. Thick arrows denote adapted angle and direction of intrasaccadic target step. Right diagrams: Same data, but replotted as angular direction change in degrees.

DISCUSSION

Generally, the results demonstrate that man and rhesus monkey can adaptively change gain as well as direction of their voluntary saccade in response to a consistent intrasaccadic target displacement. This holds for saccades of all directions, with only slight differences in the time constants of adaptation.

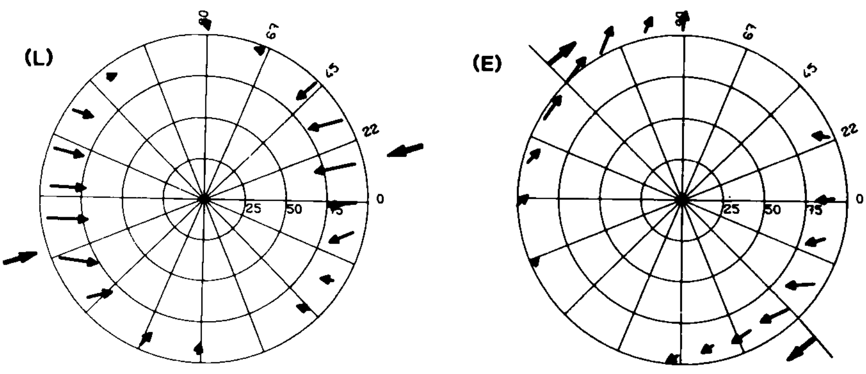
Further, we clearly showed that coding of the adaptive response does not occur in the independent x- and y coordinates of the premotor structures, nor is it associated with the directions of the extraocular muscle force. Rather, gain exhibits a sharp specificity to the direction of the movement. It follows that the existence of independent controllers specific for each movement direction has to be assumed. Thus, the results confirm the findings of Hou and Fender (1979) that computation of direction and computation of magnitude of the saccade are separate processes.

Additionally, from the results of the earlier studies on parametric adjustment (Wolf, Deubel and Hauske (1984)) it is known that within each such controller, radial gain is not specific to the eccentricity of the target. In other words, one gain parameter determines saccadic gain into a specific movement direction, independently of saccade size.

These findings are consistent with the results from recent investigations by Evinger, Kaneko and Fuchs (1981) and Gisbergen, Opstal and Schoenmakers (1985) on dynamic properties of the x- and y-components of oblique saccades, performed in cat and monkey, respectively. These authors demonstrated that the dynamics of oblique saccades cannot be described by assuming the existence of synchronized, but otherwise independent, pulse generators for horizontal and vertical components of the saccades. Rather, Gisbergen et al. (1985) suggested a model in which a vectorial pulse generator is followed by a decomposition stage which generates the horizontal and vertical components of the eye movement.

Further evidence for the existence of directionally selective subsystems in saccadic generation comes from neurophysiological studies by Hepp and Henn (1983). In single-unit recordings in the monkey paramedian pontine reticular formation they demonstrated the existence of so-called long-lead burst neurons whose firing is associated with saccades into a specific direction. Firing rates of these cells are proportional to the magnitude of the movement.

Thus, from different kinds of approaches it seems necessary to assume at a central level of oculomotor control the existence of independent "motor channels", specific for individual movement directions.



Vectorial change

Figure 7
Vectorial change. The arrows give the vectorial displacements of the mean saccade vectors due to adaptation. Data stem from monkeys E and L. Left diagram: from an Amplitude Step experiment; right: from a Direction Step experiment.

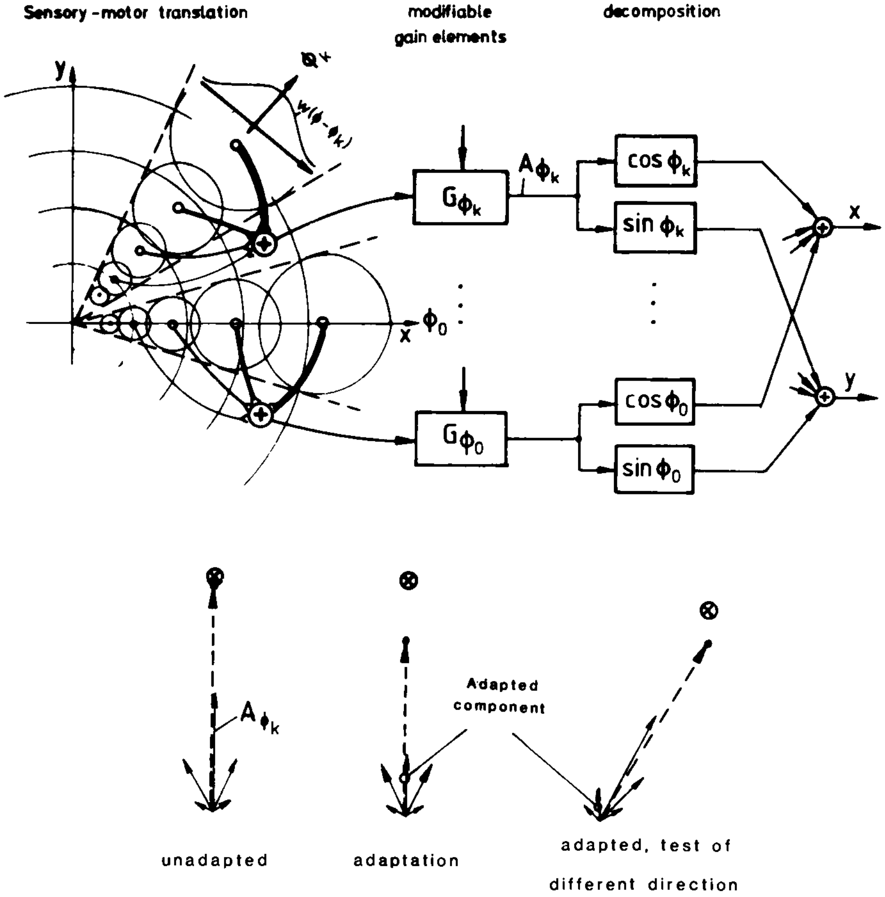


Figure 8
Conceptual model for the organization of adaptivity in the saccadic system. For each individual sector associated with the movement direction ϕ_k, a vectorial amplitude signal $A\phi_k$ is evaluated by weighted integration of the visual input signal. Radially, the weighting factor is the eccentricity of the target. In angular direction, the weighting function w ($\phi - \phi_k$) determines how tightly the individual elements are tuned. Individual gain for each movement direction is adjusted by the modifiable gain elements $G_{\phi k}$. Then, x- and y-components are determined in the decomposition stage by giving the individual vectorial signal $A_{\phi k}$ a weight cos ϕ_k and sin ϕ_k, respectively. For elements associated with the 45 deg diagonal direction, for example, these weights would be 0.707. Finally a vector sum of the contributing signals is formed. The lower part of the figure exemplifies the model predictions. Left plot: Resulting saccade vectors (dashed vectors) are composed of the vector sum of the individual subsystems. Middle plot: Upward direction is adapted. Right plot: Test of oblique direction. Since the upward element contributes less to the total vector sum, the effect of adaptation on the tested angle results in a change of radial gain as well as direction of the resulting saccade.

In the following a model is presented for adaptation of oblique saccades which correctly predicts our findings (Fig. 8). In our view, at some higher level of the sensory-motor system saccadic control is organized in independent elements of about 30 deg width, coding the eye movements into a specific direction. If the target falls into the receptive fields of one of these sections, a vectorial amplitude signal is evaluated by performing a weighted integration of the input signal. Weighting factors are: radially, the eccentricity of the target and in angular direction: a weighting function w. Consequently, the output signal A of each element is proportional to target eccentricity and intensity, and how well the target is centered on the element's axes. In other words, adjacent cones contribute less to the total saccade vector. It should be mentioned that at this level saccade angle is spatially coded, i.e. determined by which element is active; and amplitude is temporally coded, namely by the excitation of the active element. Saccadic gain is then determined by modifiable gain elements which can be adjusted independently for each sector. Finally the decomposition stage generates the x and y components of the resulting saccadic vector. It can be seen easily that changing the individual gain of one of these elements leads, for adjacent saccade angles, to a vectorial change with the direction of the adapted angle (see lower part of the figure).

[1] This study was performed while the author was Guest Researcher at the Laboratory of Sensorimotor Research of the National Institutes of Health in Bethesda, Maryland. The research was sponsored by the Deutsche Forschungsgemeinschaft (De336/1). The author wishes to thank Dr. Fred Miles for his everpresent friendly help and Drs. Jim Carl and Reuben Gellman for many delightful discussions.

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SHORT TERM ADAPTIVE MODIFICATION OF SACCADIC AMPLITUDE

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Patients with paretic ocular muscles show adaptation in both pulse and step components of the saccadic generator signals. The stimulus for step adaptation is thought to be the retinal slip which occurs when there is a mismatch between the two components; hence, the step component is adaptively modified to match the pulse component. However, the exact stimulus to pulse adaptation is not known.
In order to study saccadic adaptation in normal individuals under controlled conditions we used a technique which monitors amplitude changes induced by an adapting stimulus designed to force an error at the end of a saccadic response. This procedure produces both increasing and decreasing amplitude modifications. Results show that amplitude modifications are independent for oppositely directed movements, but are coupled over a given range of final positions, for movements in the same direction. This and other evidence supports a model in which a motor gain function is adaptively modified.

INTRODUCTION

Individual saccadic eye movements are executed without the benefit of instantaneous position information. To maintain movement accuracy in the face of changes in muscle efficiency and orbital mechanical properties some form of long term adaptive mechanism is required (Miles, 1983). In patients with paretic ocular muscles an adaptive process modifying saccadic amplitude has been discribed which follows a time course of several days (Kommerell, Olivier & Theopold, 1976; Abel, Schmidt & Dell'Osso, 1978). Monkeys with tenectomized ocular muscles showed a similar adaptation provided the cerebellum was intact (Optican & Robinson, 1980). Since the paresis in both cases undoubtedly induced a nonlinear change in muscle efficiency, the adaptive process must have developed a new gain function, that is, a gain dependent on both the initial and final positions of the movement (Optican & Robinson, 1980). Furthermore, this gain function may be separate and independently adjustable for each eye (Snow, Hove & Villis, 1985).

As the two components of the saccadic neuromuscular signal (the pulse and step components) are usually well matched, an additional adaptive mechanism mediating this balance must exist. Adaptive modification of pulse/step matching has been demonstrated in both man and monkey (Optican & Robinson, 1980; Optican & Miles, 1979). These experiments indicated that the step component is matched to the pulse, and that post-saccadic drift arising from pulse/step mismatch provides the stimulus to this adaptation. Modification of pulse/step matching has been shown in humans after short exposure to visual stimuli which induced post-saccadic drift (Optican & Miles. 1979).

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Since the step component is adaptively matched to the pulse, a change in overall saccadic amplitude requires modification of the pulse component. The stimulus for this modification is thought to be related to post-saccadic amplitude error, "but where such a complex cognitive signal might come from is not yet known" (Optican & Robinson, 1980). The cerebellum is clearly involved as mid-line lesions eliminate pulse adaptation (Optican & Robinson, 1980).

There is a growing body of experimental evidence to support the concept of a causal relationship between amplitude adaptation and post-saccadic error (McLaughlin, 1967; Wolf, Deubel & Hauske, 1983; Vossius, 1972; Weisfeld, 1972; Miller, Anstis & templeton, 1981; and Deubel, this volume). Most of these experiments used a double step stimulus protocol first described by McLaughlin (1976) in which an initial step stimulus is followed by a second error- producing step synchronized with the response to the first step. Hence, the initial saccadic response will always end in error. Using error steps oppositely directed to the initial step, McLaughlin (1967) produced a small decrease (less than 10%) in saccadic amplitude after only a few responses. Later, others (Miller, Anstis & Templeton, 1981; Wolf, Deubel & Hauske, 1983) showed that both increases and decreases in saccadic amplitude could be achieved with the error step protocol, though the increases were comparatively smaller and required more trials to achieve a maximal response. Wolf et al. (1983) also showed that changes in amplitude were proportional to initial step size suggesting the adaptation process involved a gain change. Finally, they found that adaptive modifications affected movements over a range of initial positions and amplitudes demonstrating the generality of this gain change.

In this study we use a reliable method for producing saccadic amplitude modifications to confirm previous results and to analyze behavorial features of the adaptive process. Specifically, we investigated the effective range of an adapting stimulus and the ability to produce different amplitude modifications in different response regions.

METHODS

Our experimental protocol employed two different visual stimulus patterns: an adapting stimulus and a test stimulus. The adapting stimulus followed the protocol originally discribed by McLaughlin (1967) to produce large post-saccadic errors. After an initial step change in target position, an error-producing step was generated, synchronized with the initial saccadic response (Fig.1, letter "A" in "adapting stimuli"). The error step was either in the same direction as, or opposite to, the initial step. The former we call positive error steps and the latter negative error steps. Both stimulus generation and data acquisition were under microprocessor control. After generating the initial step, the microprocessor monitored the ensuing ocular response, and issued the error step a fixed delay after the onset of the movement. Saccadic onset was detected using a velocity threshold criterion which was set during the initial responses of an experimental run. The test stimulus was used to monitor modifications in saccadic amplitude. It consisted of an initial step followed by target disappearance (Fig. 1 "tests"). This disappearance was also synchronized with the saccadic movement and was employed to reduce secondary saccades (Prablanc, Masse & Echallier, 1978) which would hinder the analysis of any slow post-saccadic movement. After 1.5 seconds the target reappeared at the endpoint position to provide a calibration point (Fig. 1 "test").

The stimulus target was binocularly viewed at a distance of 57.0 cm. and consisted of a 0.5 degree bright spot projected on an otherwise dark background. The spot contained a dark central cross to provide a small fixation point especially useful for calibration. Spot position was controlled by a mirror galvanometer (General Scanning) driven by the microprocessor. The stimulus device had a maximum range of +/- 20.0 deg.

Horizontal eye movements were recorded in the left eye only, using the differential infrared reflection technique. To insure appropriate stimulus timing all responses were presented on the interactive display in conjunction with an error step timing mark. However, only the test responses were recorded on disk for subsequent analysis. Eight subjects were used for this experiment.

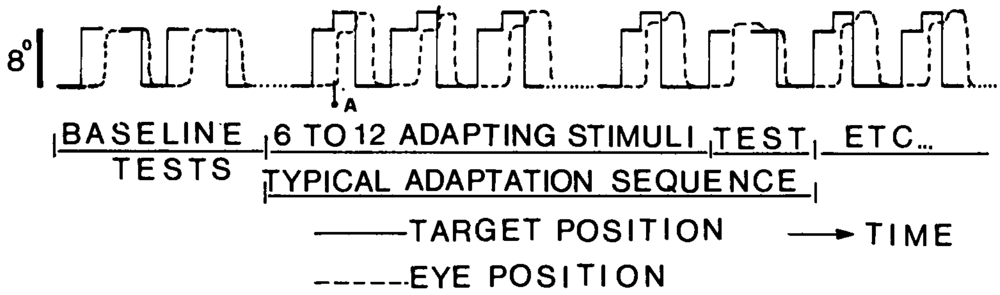

Figure 1. Time trace of an adaptive sequence consisting of a number of adapting stimuli followed by one test stimulus shown embedded in an experimental run. An adaptive stimulus consists of an initial step followed by a response-synchronized error step while a test stimulus consists of an initial step of the target spot, followed by a response-synchronized disappearance of the target spot with a reappearance 1.5 sec. after the initial step. Typical responses to such a stimulus pattern are shown superimposed on the stimulus trace.

A typical experimental run was composed of a series of from 10 to 60 adaptation sequences (Fig. 1, "adaptation sequence"). An adaptation sequence consisted of approximately 10 identical adapting stimuli followed by a test stimulus; however, in a few runs two different adapting stimuli were intermixed. While each adaptation sequence had only one test stimulus, most runs included adaptation sequences with a variety of test stimuli to establish the range of an adaptive modification. Though error step size remained constant within an adaptation sequence, in some runs the error step size was modified between adaptation sequences. Each stimulus, whether adapting or test, began with a horizontal step change from the central position. Both onset time and direction were randomized to prevent prediction, the latter achieved by occasionally introducing an irrelevant step stimulus into an adaptation sequence. Each experimental run was preceded by a baseline series of tests (Fig.1, "baseline tests").

The analysis procedure employed the interactive display and an operator to identify critical features of each test response: initial baseline level, saccade onset time, response amplitude, region of post-saccadic drift, latency and amplitude of secondary saccades (if any), and final calibration position. While somewhat tedious, this analysis procedure, using human pattern recognition skills, provided consistently reliable data. Using these critical features the microprocessor calculated the response latency (in ms), saccadic amplitude (in deg.), velocity of post-saccadic drift (deg./s), and the amplitude and latency of any secondary saccades. All amplitudes were calculated using the initial baseline and final calibration as reference points; hence, each response was individually calibrated. For each of the individual response parameters, averages and standard deviations were calculated over response groups.

RESULTS

Preliminary experiments confirmed that some degree of saccadic amplitude modification could always be achieved using the error step paradigm. These early results also indicated that a progressive increase in error step amplitude was no more effective in producing adaptive changes than a fixed error step of the same maximum value, except for very large error step values. That is, for error steps less than, or equal to 50% of the initial step size, approximately the same number of trials were required for a maximal change if the error step was progressively increased, or simply fixed at the final value. For error steps between 50% and 100% of the initial step size, a two-stage progression produced slightly greater adaptation over the same time period. Error steps greater than 100% of the initial size were not attempted due to range limitations of the stimulus device.

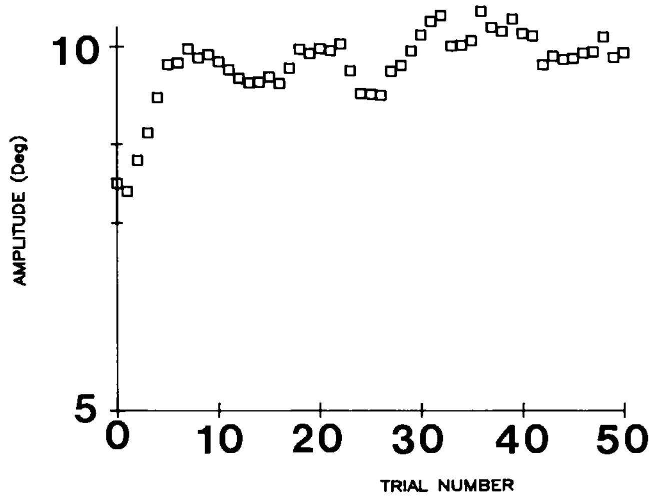

Figure 2. Amplitudes of initial saccadic response to an 8.0 deg. test stimulus plotted as a function of adaptive sequence or "trial" number. In each trial the test stimulus was preceded by approximately 10 adaptive stimuli featuring an 8.0 deg. initial step followed by a 4.0 deg. error step. The average and standard deviation of 20 normal 8.0 deg. step responses is shown at trial 0. Data were filtered using a 3 point running average.

The time course of amplitude modification to a series of identical adaptation sequences with a 50% error step is shown in fig. 2. Each point represents the test response of one sequence in the series. Specifically, the test stimulus was 8.0 deg. and the adapting stimulus consisted of an 8.0 deg. initial step and 4.0 deg. error step. The point at trial number zero shows the average and standard deviation of 20 baseline trials. As mentioned in the Methods section all experimental runs included random single step stimuli of varying magnitudes and directions to prevent prediction or some form of task specific motor learning. The responses of Fig. 2 show a rapid increase in response amplitude to identical test stimuli, reaching a maximum increase of around 2.0 deg. after 7 adaptive sequences (ie, approximately 70 adaptive stimuli). This modification is sightly larger and occurs somewhat more rapidly than that reported by Wolf et al (1983); however, the maximal increase is still only half the error step size, the change required for complete compensation to the 4.0 deg. error step.

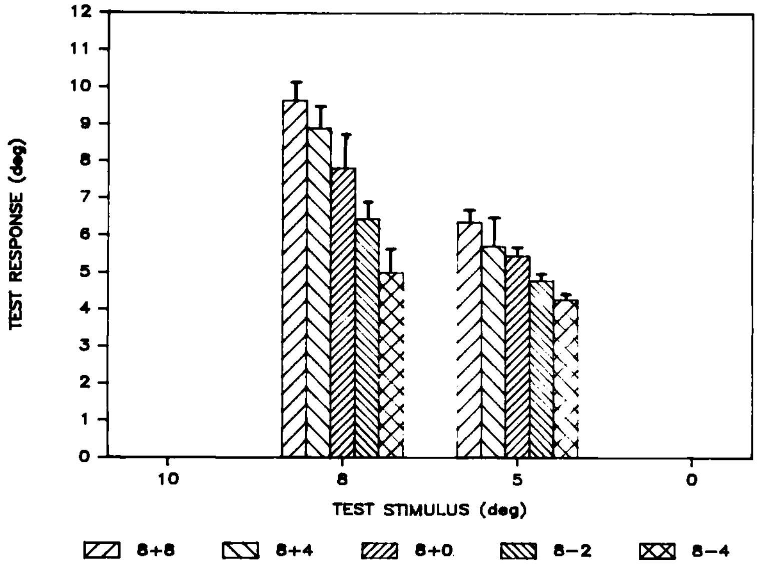

Figure 3. Test response amplitudes as a function of test stimulus amplitudes for several different adaptive stimuli. Each bar shows test response average and standard deviation over approximately 20 adaptive sequences. The adaptive sequences consisted of 8.0 deg. initial steps followed by error steps of 0.0 (baseline), 4.0, 8.0, - 2.0, and - 4.0 deg. error steps.

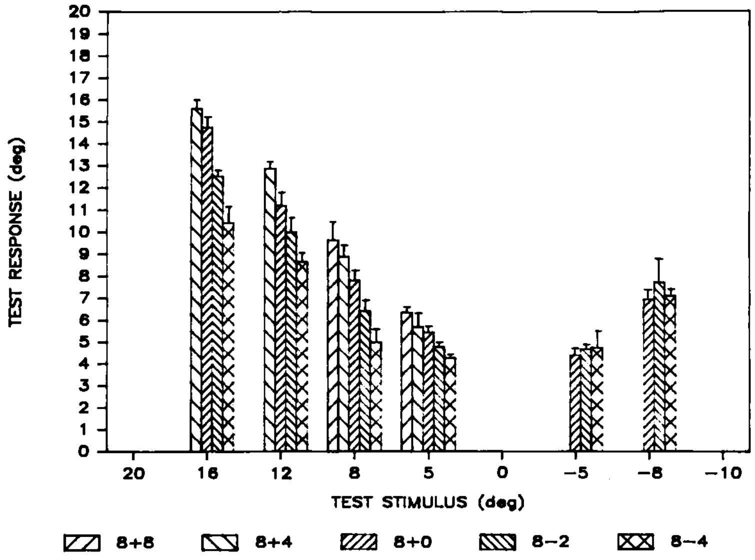

Figure 4. Test responses to the same conditions as in figure 3, but over a wider range of stimulus amplitudes including both leftward (positive) and rightward (negative) test stimuli.

The amplitude modification is directly related to the error step size. Fig. 3 shows the averages and standard deviations of test responses to adaptation sequences with several different error steps. The center bar of each group represents the baseline test response (0.0 deg. error steps) while the bars left of center are responses produced by 4.0 and 8.0 deg. error steps respectively. The initial adapting step in all cases was 8.0 deg. Each bar represents an average of approximately 20 adaptation sequences with standard deviations as shown. A roughly linear relationship between adaptive change and error step size is seen with the maximum change around half the error step size.

Error steps which are directed opposite to the initial step will produce decreases in response amplitude (McLaughlin, 1967; Miller, Anstis & Templeton, 1981; Wolf, Dubel & Hauske, 1983). The bars to the right of center in Fig. 3 present the averages and standard deviations of test responses to adapting stimuli with negative error steps. These show an approximately linear decrease in test response amplitude as the (negative) error step increases. In fact, as noted previously (Miller, Anstis & Templeton, 1981; Wolf, Deubel & Hauske, 1983), the changes are proportionately larger than those found with increasing modification, approaching 75% of error step size.

Though our adapting stimulus is fixed in terms of initial position, initial step size and error step size, it modifies saccadic responses over a range of amplitudes. In Fig. 3, the responses to 5.0 deg. test stimuli show the same general amplitude modification as the 8.0 deg. responses. This generality of amplitude modification is shown clearly in Fig. 4 where a broader range of test response amplitudes is presented. Both positive and negative error steps induce their characteristic modifications at all test amplitudes shown provided they are in the same direction as the adapting stimulus (leftward). As previously reported (Miller et al, 1981; Wolf et al., 1983), test responses in the opposite direction (rightward for Fig. 4) are not affected. Also, while the modification is general, change in the smallest (5.0 deg.) test responses were not as great as those closer to the adapting stimulus amplitude.

The data of Figs. 3 and 4, indicate that an adaptive stimulus influences all movements in the same direction, or at least in the same general response region, showing a form of "adaptive coupling". Oppositely directed movements are not affected (Fig. 4) and show "adaptive independence". If response regions are truely independent, we should be able to modify them differentially using two or more adapting stimuli intermixed within an adaptation sequence. Using different adapting stimuli for leftward and rightward movements we were able to increase or decrease amplitudes in the two directions independently. In Fig. 5a the two adapting stimuli were structured to increase responses in their respective directions that is, an initial rightward or leftward step is followed by an error step (4.0 or 8.0 degrees) in the same direction. The resultant modification was an increase in the test responses in both directions though the change was less than that obtained when only one adapting stimulus is employed (Fig. 3) probably due to the reduction within an adaptation sequence of a given stimulus type. Conversely, using negative error steps in one direction and positive error steps in the other, it is possible to increase movements in one direction while decreasing the movements in the other. In Fig. 5b leftward movements are increased by an adapting stimulus with positive error steps while rightward movements are decreased by an adapting stimulus with negative error steps. Taken together, these results indicate that movements directed to the left and to the right of center may be independently modified.

Adaptive coupling is demonstrated when two conflicting adapting stimuli are directed to the same side. Adapting stimuli having 8.0 deg. initial steps and 4.0 or 8.0 deg. error steps were intermixed with stimuli having 5 deg. initial steps and -1.0 or -2.0 deg. error steps, both to the left. The results in Fig. 6 show that the 5.0 deg. test responses decrease as expected due to the adapting

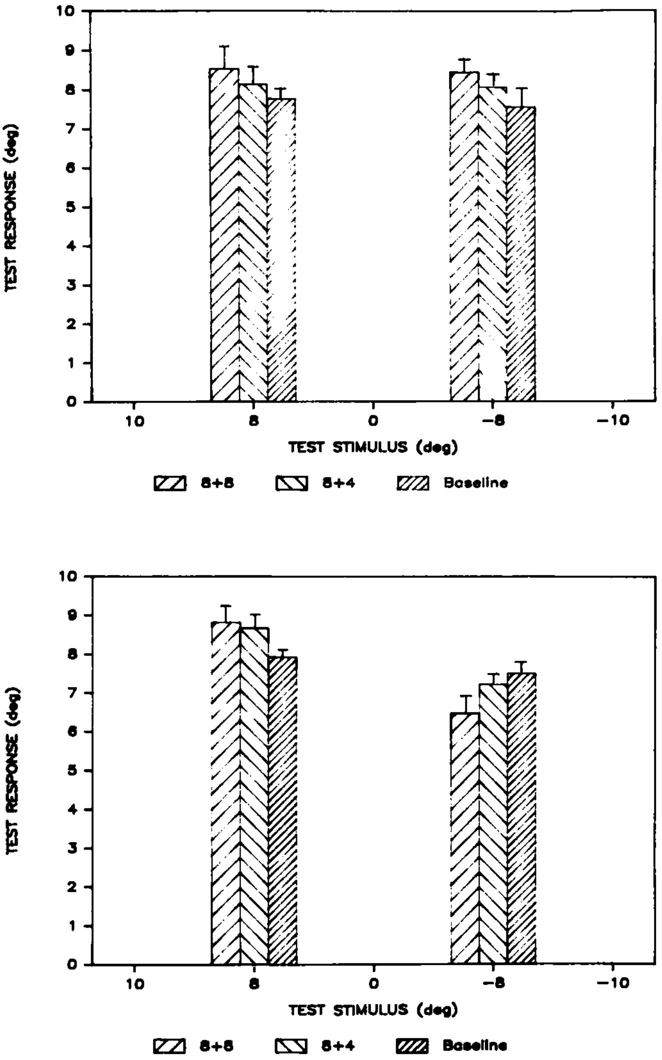

Figure 5. Averages and standard deviations of test responses as presented in Fig. 3 to adaptive trials containing two different adaptive stimuli. a: Test responses to a mixture of leftward and rightward stimuli with 4.0 and 8.0 deg. error steps in the same direction as the initial step (also 8.0 deg.). b: Test responses to combination of leftward and rightward adaptive stimuli as in a; however, the rightward adaptive stimulus consisted of 2.0 and 4.0 deg. error steps in the direction opposite to the initial movement.

stimulus with negative error steps. However, the 8.0 deg. test responses show only a slight increase due to the 4 deg. positive error step which is paired with the -1.0 deg. error step (middle bar) and a decrease with the 8.0 deg. error step which is paired with the -2.0 deg. error step (righthand bar). This decrease is likely due to the greater effectiveness of negative error steps noted earlier. The results of Fig. 6 indicate that independent modification of similarly directed movements is modest at best, at least for response ranges close to one another (in this case 5.0 and 8.0 deg.).

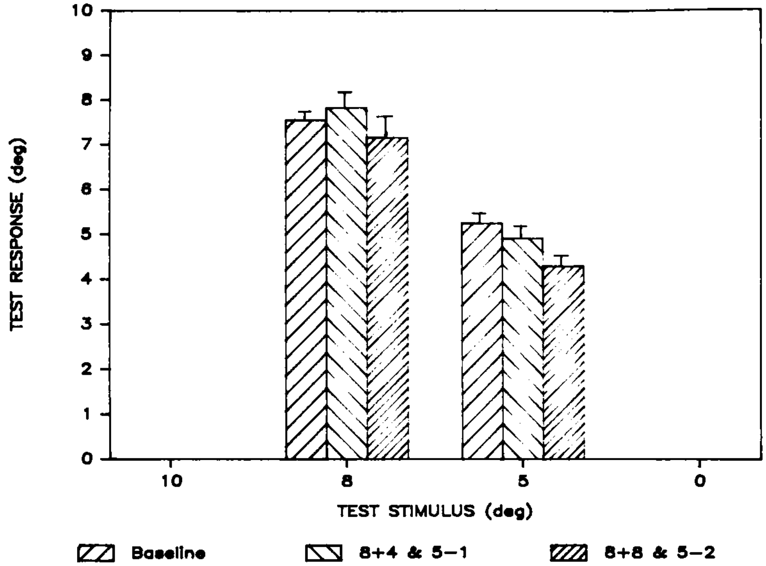

Figure 6. Test responses produced from 20 adaptive trials each containing two different, but similarly directed (leftward) adaptive stimuli: an 8.0 deg. initial step followed by a 4.0 or 8.0 deg. error step, and a 5.0 deg. initial step followed by an oppositely directed 1.0 or 2.0 deg. error step. Adaptive stimuli containing 4.0 and -1.0 deg. error steps were paired in the same adapting sequence as were adaptive stimuli containing 8.0 and -2.0 deg. error steps.

DISCUSSION

Our results confirm the ability to produce short term adaptive modification of saccadic amplitude using stimuli which produce large post-saccadic error. We believe the results indicate true adaptation, not motor learning of a specific tracking task. Evidence for adaptation includes the incremental increase in response amplitudes, the incomplete error compensation and the modification of all similarly directed movements by a single adaptive stimulus (adaptive coupling). In addition, an after effect of up to 75% of the original modification was occasionally observed several hours after the experiment.

Wolf, Deubel and Hauske (1983) demonstrated that when error step size is fixed the adaptive modification is a function of the initial step size. In Fig. 3 we show that the modification is also dependent on the magnitude of the error step. This suggests that post-saccadic error provides a direct drive to the adaptive process. For all experiments shown, the error step was generated 10 to 15 msec. after the onset of the saccade, placing it well into the first half of the movement. (It is interesting to note that, in this position, positive error steps up to half the size of the initial step were not consciously perceived.) The influence of error step timing was not comprehensively studied, but during early runs we noted that error steps placed at the end of the movement were slightly less effective in producing amplitude modification. Current work includes a detailed study of error step timing since this may provide clues to the specific features of post-saccadic error used to drive the adaptive process.

While post-saccadic drift was analyzed in each test response, no significant trends were found. If the modifications observed are due initially to a change in the pulse component, increased post-saccadic drift (either upward or downward depending on the direction of the modification) would be expected. It is possible that amplitude modification is sufficiently slow to allow the step component to follow the pulse component with negligible (or undetectable) error. Future work will include a more detailed analysis of the early adaptive response where the modification is most rapid.

The general influence of adaptation over a range of amplitudes was suggested in the "transfer" experiments of Miller et al (1981); however, their results were not statistically significant. Wolf, Deubel & Hauske (1983) also showed amplitude modification occuring over a range of initial positions and amplitudes, but in their paradigm the adapting stimuli also had a wide range of initial positions. In the data of figures 3 and 4 we demonstrate that general modification can be produced with only one type of adapting stimulus, a phenomenon we term adaptive coupling. The adaptive coupling experiments (Figs. 5 and 6) show that responses in the same region are coupled and can not be modified without influencing other regional responses, while oppositely directed movements show complete independence. Two questions emerge from these experiments: how elastic is the coupling; and, is the independence based on direction (leftward versus rightward), or sidedness (left versus right of center)?

To the first question we note that the adaptation found in patients with muscle paresis could not be achieved with a single gain change. Hence, this adaptation requires a variable, movement dependent gain change (or gain function), indicating some elasticity must exist even for closely spaced movements in the same direction. Indeed, the data of fig. 6 suggest some flexibility in the coupling. The extent of this flexibility is currently being examined.

To address the second question some experiments were recently performed which used test stimuli with nonzero initial positions. Results show that a single adapting stimulus can modify movements originating on either side of the center position as long as they are in the same direction, suggesting that independence is based on direction not sidedness.

CONCLUSION

In summary, the error step paradigm described here provides a useful tool for studying short term adaptation of saccadic amplitude in normal subjects under tightly controlled stimulus conditions. The adaptation so obtained is progressive, but limited to 50% to 75% of that required for full compensation, at least during reasonable experimental time periods. With the appropriate adapting stimulus, both increased and decreased response amplitudes can be obtained, but amplitude decreases are larger and achieved more rapidly than increases. The adaptive modification applies to all movements in a given region to a given side, but there is independence between movements oppositely directed. Finally, while all movements to one side are influenced by this adaptive modification, some flexibility exists to permit gain variation as a function of movement range.

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EYE MOVEMENTS: From Physiology to Cognition
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ADAPTIVE OPTIMIZATION OF EYE-HEAD COORDINATION WITH DEGRADED PERIPHERAL VISION (*)

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In head-free visual target tracking, the eyes attain the target while the head is still moving. Visual discrimination may start as soon as gaze is stabilized. When peripheral vision is degraded by systems placed in front of the eyes and carried by the head such as spectacles with degraded peripheral optics, foveal discrimination will not be possible unless the head moves towards the target to recenter the eyes through the optical area of clear vision. Thus, an additional delay in visual discrimination is to be expected with degraded peripheral optics. We have investigated the adaptive changes in eye-head coordination resulting from continuous wearing of glasses which alter peripheral vision, in visual target discrimination tasks. The results show that adaptive processes develop which lead, within a few days to a few weeks, to partial recovery of visual motor performance. Early changes include, as predicted, a decrease of head movement delay and an increase of head velocity.

INTRODUCTION

During head movements, the eyes must be held stationary in space to provide clear vision of the fixated object. Spatial stabilization of the gaze is accomplished by a rotational movement of the eyes which is counter to that of the head and compensates for it. These eye movements are under direct control of the vestibular system but are influenced by visual and neck proprioceptive inputs. In the opposite situation in which a fast moving target is to be tracked, two patterns of responses may be evoked, in which either the eyes alone or the eyes and the head are involved.

Eye alone tracking: If the head is immobilized or if the target jump is within 5 to 10 degrees, the response consists of a saccade bringing the fovea onto the target. Visual discrimination may occur as soon as the eyes reach the target, that is within 300 to 400 ms (200 to 300 ms saccadic reaction time, 100 ms eye movement time).

Eye-head coordination in normal vision: when the head is free to move and target amplitude exceeds 10 degrees, tracking of visual targets is accomplished by a more complex sequence of eye and head movements. However, some subjects do not move the head - or only on occasion - even for large amplitude target displacements, particularly if the target is likely to move alternatively between two positions or only remains for a short period in the new position. When a target of interest steps to a peripheral position and remains stationary for a long period, a large amplitude saccade is generally generated, followed later by a slow head movement of an amplitude almost equal to the target eccentricity so that the eyes are recentered in the orbits.

The most common response to a large amplitude target displacement consists of a sequence of coordinated eye-head movements. A main saccade moves the eyes over 90% of the target eccentricity, followed by a secondary saccade which captures the target (Fig. 1, top). In the mean time, the head has begun its rotation towards the target. The delay of the first saccade is between 150 to 300 ms while that of the secondary saccade is of the order of 100 milliseconds or less. Four different types of eye-head movement patterns have been described by Zangemeister & Stark (1981). The types are defined in terms of delay between the eye and the head. The most common type (Type III A) observed in non-time-optimal eye-head tracking and in normal visual scanning situations has been studied in details in both man (Bartz, 1965; Zangemeister & Stark, 1981) and monkey (Bizzi, Kalil & Tagliasco, 1971; Morasso, Bizzi & Dichgans, 1973;) It consists of a pattern in which the head starts moving with the eyes or shortly

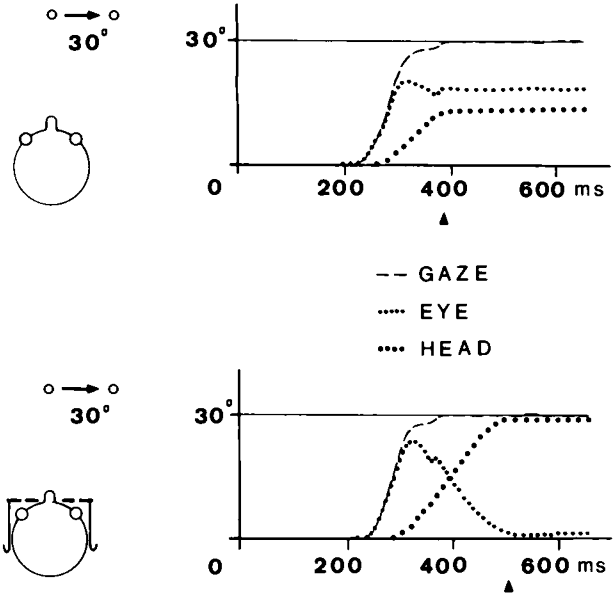

Fig. 1: Typical eye-head movement sequence in usual tracking of a 30 degree target with normal (above) and degraded peripheral vision (below). Gaze, the position of the eyes in space, is also represented. The optical device used to degrade vision is a set of neutral lenses made translucent throughout except for a narrow vertical zone centered on the eye axis.

after as in Fig. 1 (top). Since the head, because of its inertia, has lower dynamics than the eye and does not reach high velocity, the eyes attain the target while the head is still moving. Visual discrimination of the target, if attempted, may start from this instant (arrow) since the eyes remain stabilized in space (stationary gaze) during the remaining head rotation by full activation of the vestibulo-ocular reflex (VOR). The VOR is usually defined by its gain, the ratio of eye over head angular velocity. In eye-head tracking of distant targets, the VOR gain is exactly unity as soon as the eyes reach the target, providing gaze stability during the remaining head movement. Note that stabilization of gaze may also be assisted by the opto-kinetic system. In the most common type (III A) of eye-head tracking, head movement amplitude is roughly 40 to 70% of target displacement so that in the final steady state, 30 to 60% of gaze change is produced by a deviation of the eyes in the orbits.

Mention was made earlier that in normal situations, gaze remained stationary during the last portion of head rotation. However, fixation may be interrupted by small saccades, generally opposite to the slow phase eye movement, which correct errors in position. These small saccades are different from the secondary saccades which are part of a systematically pre-programmed double-saccade response. They are usually observed in a variety of experimental protocols involving distorsion of the visual input and as a result, mislocation of the target and/or miscalibration of the VOR gain. It is to be mentioned that the mismatch between retinal displacement and the outflowing corollary discharge signals (Sperry, 1950; Stark & Bridgeman, 1983) gives rise to the illusory perception of target instability (space inconstancy) and possibly to localization errors in unstructured visual fields. Loss of space constancy also occurs in high velocity eye-head tracking and in normal velocity tracking when the VOR-induced eye movements do not match head movements. Such mismatches are also observed in situations in which subjects wear magnifying lenses (Gauthier & Robinson, 1975) or reversing prisms (Gonshor & Melvill Jones, 1973; Stratton, 1897). Studies have shown that, in these vision distorted situations, adaptive modifications of the VOR gain, progressively restores visual world stability (Gauthier & Robinson, 1975; Gonshor & Melvill Jones, 1973; Berthoz & Melvill Jones, 1985).

Eye-head coordination with degraded peripheral vision: Fine visual discrimination can only be achieved by the fovea. This implies that peripherally presented targets require precise eye movements to bring the image into the fovea and stabilize it. When peripheral vision is degraded by systems placed in front of the eyes and carried by the head, such as spectacles with degraded peripheral optics, foveal capture may be realized with more or less precision, but visual discrimination will not be possible unless the head moves towards the target in order to recenter the eyes through the area of clear vision. In such conditions, visual tracking of peripherally presented targets will systematically require both eye and head movements. If the zone of clear vision is narrow, the sequence of movements is likely to resemble that presented in Fig. 1 (bottom). The amplitude of the head movement is practically equal to the eccentricity of the target. Fine visual discrimination may begin only when the eye returns to the optical zone of clear vision, as indicated by the arrow, which occurs after a delay of 500 milliseconds or more. This is to be contrasted with the normal vision condition in which discrimination can start as soon as the eye reaches the target (indicated by the arrow, in the upper part of Fig.1). Thus the additional delay (of the order of 100 to 300 milliseconds) in discrimination time associated with degraded peripheral vision may be attributed primarily to the duration of the necessary head movement.

Adaptation of eye-head coordination to degraded peripheral vision: The observed augmentation of 100 to 300 milliseconds of discrimination time due to degraded peripheral vision will cause a serious slowing in reading and visual exploration tasks. However, one may suspect that the central nervous system will attempt to optimize the coordination of eye and head movements to partially restore the performance of the visuo-oculo-motor-system. Two non exclusive adaptive changes may be expected: the head movement delay with respect to the target may be systematically decreased so that the eye-head movement type will tend to become regular type III (consistent head movement delay shorter than that of eye movement); or, there may be an increase in head velocity.

To address these problems, we designed an experiment to compare eye-head movement interaction in normal subjects and in subjects fitted with glasses which alter peripheral vision. The alteration was caused by a thin layer light-diffusing oil delimiting a narrow zone of clear optics along the vertical axis of each optically neutral lens. This "optical modulation" simulates that of progressive lenses in the lateral fields when the subject views objects at intermediate distance. Such lenses are commonly used in the correction of presbyopia. Observations show that discomfort, of sensorimotor and perceptual origins, may result during the first few days of exposure. One may suspect these problems to be closely related to those described above and observed in experiments using magnifying lenses or reversing prisms. Hence, it is likely that similar adaptive mechanisms restoring normal performance in these experimental situations will be activated in subjects wearing progressive lenses. Indeed, the results presented here, dealing with discrimination through degraded peripheral visual fields, show that adaptation leads to partial recovery of visual motor performance.

METHODS

The experimental arrangement allowed the subject to be seated in front of a screen on which were placed a central fixation target FP and two discrimination targets T1, T2, 30 degrees on both sides of the center target (Fig.2). The inset

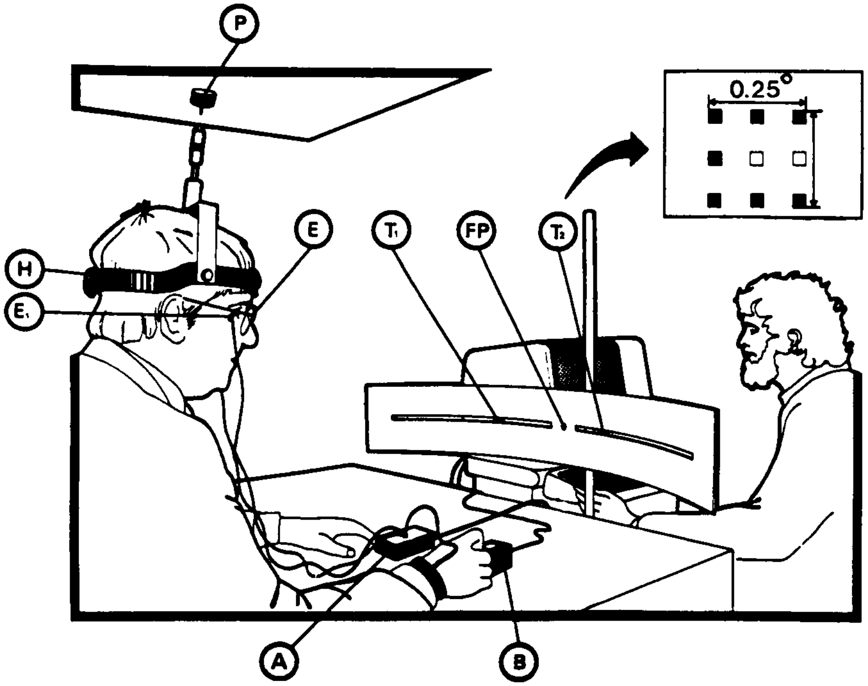

Fig. 2: Experimental arrangement.

drawing shows the LED matrix used as discrimination targets. Seen by the subject, on the screen placed at 65 cm, the target was a square whose side was 0.25 degrees. A mini-computer (MINC 11/23) activated one matrix to light a "C" whose aperture, 11 minutes of arc in size, was randomly oriented to 0, 90, 180 or 270 degrees.

The horizontal component of head movement was measured with a 60 degree potentiometer,P, attached to a helmet. The potentiometer base was mounted on a X-Y sliding board through a homokinetic joint. Horizontal eye movements were monitored by DC coupled EOG electrodes placed on the zigomatic arch of each eye E1. Eye and head movement signals were stored in the computer as well as the switch signal used by the subject to indicate his response. Eye, E, and head, H, movement signals were separately calibrated.

The protocol sequence (Fig. 3) started with the subject fixating the central illuminated target. A blink of that central target FP signaled the subject that extinction would occur 500 milliseconds later and that, concomittently, one of the two discrimination targets T1 or T2 would randomly be activated. The subject was requested to respond as soon as possible, pushing the switch A or B and telling the experimenter his observed orientation of the "C". A maximal period of three seconds was allowed for the mandatory response. No instruction was

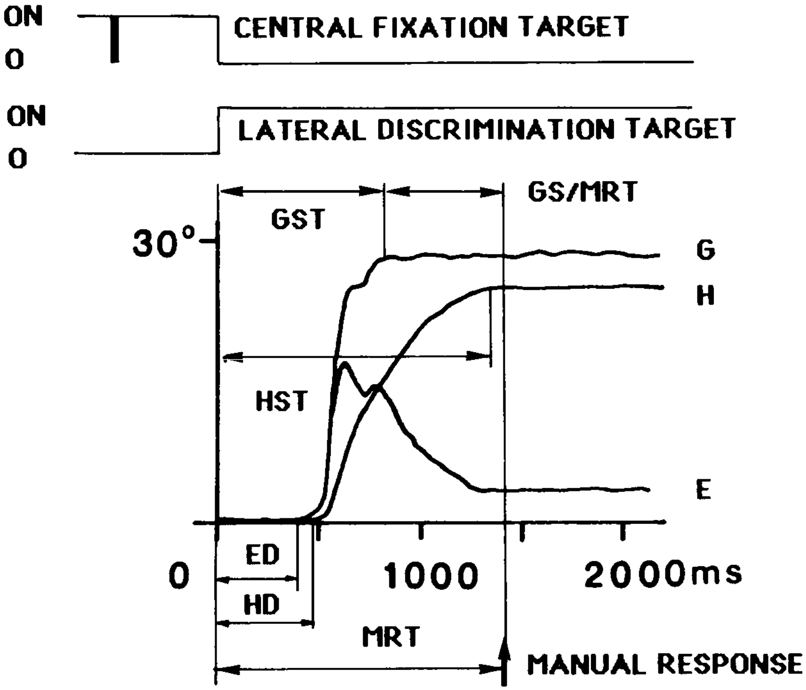

Fig. 3: Experimental protocol and time characteristics selected for analysis of the discrimination performance.

provided as to whether the subject should or not move the head to accomplish the task. He was only told to answer rapidly and behave as he normally would to view objects in the peripheral fields.

A series of discrimination trials were obtained from 14 subjects with both normal vision and with degraded peripheral fields. Some normal subjects were fitted with lenses on which oil was deposited to restrict clear vision to a 4 millimeter vertical zone, at the center of each lens. Some presbyopic subjects were tested with their progressive lenses the first day and after 2 to 3 weeks of continuous wearing in order to study the adaptive effects of prolonged exposure. Computer analysis of performance was conducted after the experiment. It consisted of comparing the average performance in the various conditions through measures such as the gaze stabilization time (GST), that is, the time for gaze to acquire the target; gaze stabilization to manual response time (GS/MRT); head stabilization time (HST) which is equal to eye stabilization time; eye and head movement delays, (ED and HD respectively) and the overall manual response time (MRT) as signaled by the switch (Fig. 3). All these factors as well as maximum eye and head movement amplitudes were essential to understand how eye and head movements interact in normal and vision altered situations and how adaptive processes optimize the performance in spite of visual constraints. In this report, we shall concentrate almost exclusively on overall response time (MRT).

RESULTS

Normal viewing condition: A first series of trials was performed under normal visual conditions to demonstrate the normal behavior of each subject in the

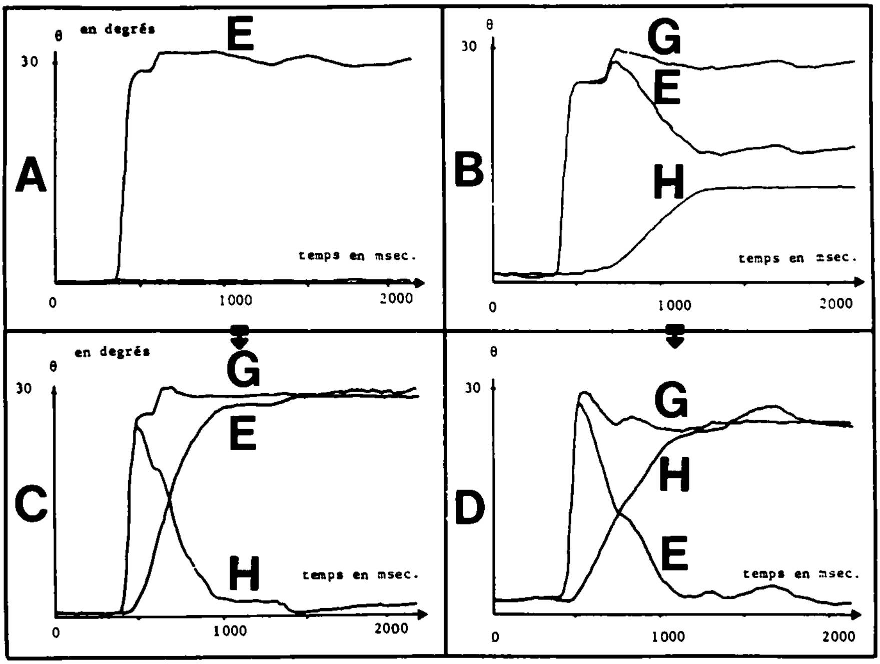

Fig. 4: Typical gaze (G), head (H), and eye (E) movement recordings. Normal (A and B) and degraded peripheral vision (C and D).

discrimination task. In spite of the large eccentricity (30 degrees) of lateral targets, 80% of the subjects did not move the head to discriminate the orientation of the "C". A typical response (Fig. 4, A) showed the gaze deviation to be produced by a large saccade with amplitude equal to target eccentricity.

The eye movement delay (ED) was about 300 milliseconds. The other 20% of the subjects produced a more classic (type III A) eye-head movement sequence (Fig. 4, B). The main saccade had a delay (ED) of about 300 milliseconds and the head started to move (HD) about 100 milliseconds later. In all subjects tested under the normal viewing condition, these delays and the durations of the main and secondary saccades were similar. The head movement amplitude was of the order of 40% of the target eccentricity so that during visual discrimination, the eyes were 10 to 15 degrees away from the primary position. In all subjects (Fig. 4, A and B) gaze was stabilized after a GST of 500 to 700 milliseconds.

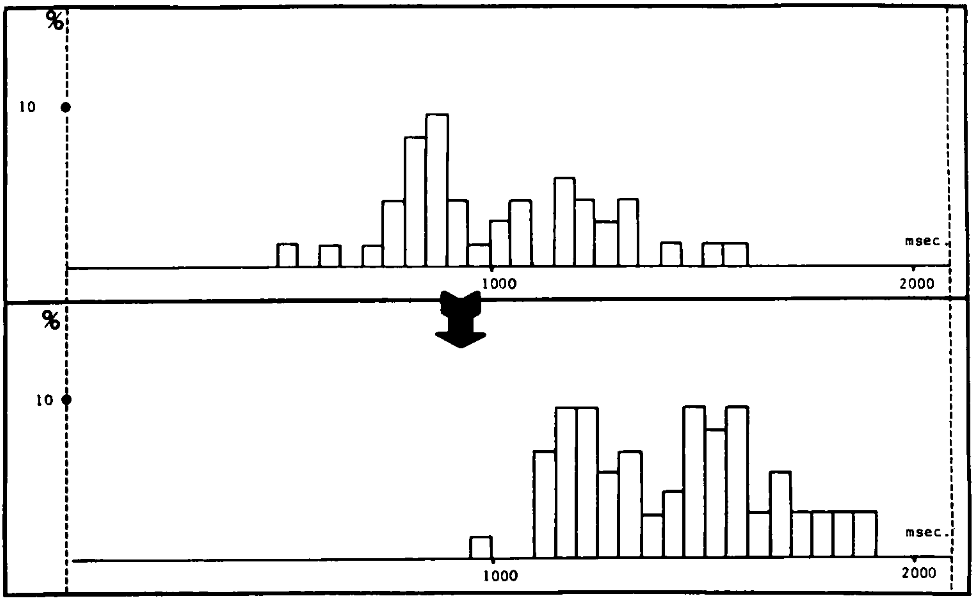

Fig. 5 Overall manual response time histograms. Discrimination task carried out with normal (above) and degraded peripheral vision (below).

Degraded peripheral vision: As predicted, whether or not they moved the head in the normal viewing condition, all subjects were forced to make large amplitude head movements in order to discriminate the target viewed through the optically modulated lenses with degraded peripheral fields. In fact, the head movement amplitude was about equal to target eccentricity. Typical records from a subject who responded with no head movement in normal vision (Fig. 4, C) and from a subject who responded with combined eye and head movements in normal vision (Fig. 4, D) showed early changes in gaze behavior. Head movement delays were shorter and velocities larger than those recorded in normal vision. As stated earlier, these were the two possible ways of decreasing the overall response time. In fact, from the recordings shown here, visual discrimination could only begin 900 to 1200 milliseconds after target presentation, that is, when the eyes were recentered in their orbits. Recall that the zone of clear vision through the lenses was fairly narrow. As a result, the manual response time (MRT) was considerably delayed as compared to normal vision conditions.

Histograms of response times in normal (Fig. 5, upper) and degraded peripheral vision (Fig. 5, lower) show the difference between the mean response times in the two situations to be 400 to 500 milliseconds. From the lower records of Fig. 4 one may observe that this time is practically equal to head movement time (HST-HD).

Adaptation of eye-head movement coordination to degraded peripheral vision: As mentioned earlier, rapid changes occurred to optimize the response with degraded peripheral vision. Similar early changes were observed in subjects fitted with progressive lenses. Further adaptive changes occurred gradually in one to three weeks. They consisted in a further decrease of the head movement delay which became practically identical to that of the eyes and a further but slight increase of the head velocity (Fig. 6). In practically all adapted progressive lens wearers, a decrease of head movement amplitude, and a correspondingly larger eye eccentricity in final position, was also observed. Gaze, eye and head positions became more stable once the target was captured. All these adaptive changes were beneficial and the average overall discrimination time (MRT) decreased by 250 milliseconds as a result of continuing adaptation over two to three weeks.

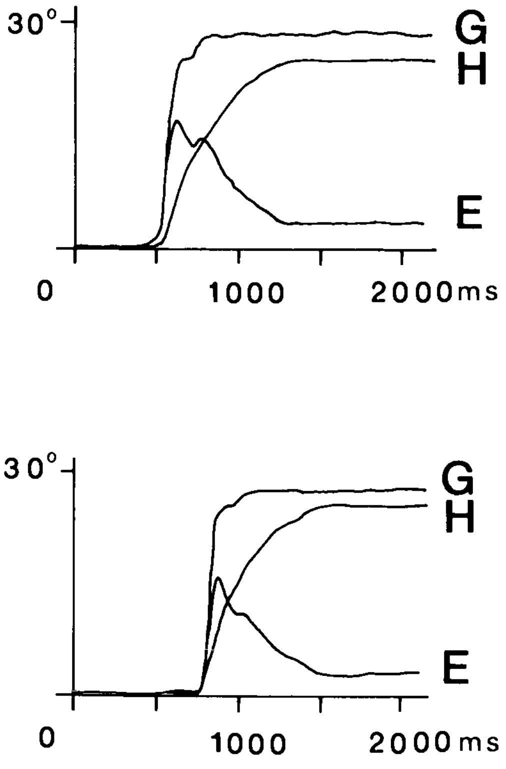

Fig. 6: Gaze (G) eye (E) head (H) movement sequences. Typical responses from two subjects adapted to progressive lenses.

DISCUSSION

All subjects, whether or not they moved their head in normal vision, had to move the head when peripheral vision was degraded. The narrow zone of clear vision in the lenses forced head movement amplitude to be equal to target eccentricity. The cost of moving the head, in terms of time, represented in our experimental protocol about 30% of the overall manual response time. Since the saccadic characteristics do not change much, the increase of response time was essentially due to head motion time for subjects who did not move their heads in normal vision. Also, for subjects who did move their heads in normal vision, an increase in head movement time was the direct result of an increase of head movement amplitude.

The marked increased of the overall response time should not be misinterpreted. The task involved discrimination of small targets positioned at a large eccentricity (30 degrees). The dynamics of the head (Sugie & Watakuwa, 1970; Dichgans, Bizzi, Morasso & Tagliasco, 1974; Morasso, Bizzi & Dichgans, 1980; Reber & Goldsmith, 1979; Zangemeister & Stark, 1981; Zangemeister, Jones & Stark, 1980; Gauthier, Martin & Stark, 1986) are such that large head movements require long times. Furthermore, the task was not executed in a time optimal protocol. This also explains the large saccadic delay observed (over 300 milliseconds), as compared to 160 to 200 milliseconds in fast-response, random target protocols.

An important fact was that within a few trials the subjects had already attempted to optimize ocular and cephalic responses to decrease the overall response time. As predicted, the head movement delay became shorter and head velocity higher. Most coordinated eye-head movements tend to be of type III A. In fact, type III A as defined by Zangemeister & Stark (1981) constitute a broad class, grouping eye-head interactions with various a eye-to-head delays. In all these cases, the VOR stabilizes the eyes on the target during part or all of the head movement.

Analysis of the data from subjects fitted with progressive lenses showed that the eye-head movement sequence was very similar to that of normal subjects fitted with lenses with degraded peripheral optics. This allow us to study in detail adaptive processes taking place during the early minutes and days of exposure, and also to compare various strategies and modes of eye-head interaction in normal subjects and presbyopes wearing progressives lenses. Fast adaptive protocols may be found for progressive lens wearers and in turn, provide information to optimize the structure and design of corrective lenses.

Long term wearing of progressive lenses brought about further adaptive changes (Fig. 6) as evidenced in discrimination tasks occurring over one to three weeks. They are the result of further decreases in eye to head delay: eye and head movements become practically synchronous and showed a higher stabilization of gaze. Also, a more efficient use of the lenses was suggested by the observation that in most eye-head movement sequences, the head movement amplitude was not more than 80% of target eccentricity, in contrast to amplitudes about equal to target eccentricity in early trials of the first day of wearing. It follows that adaptive optimization of eye-head coordination sequences is accompanied by a sensory adaptation in the use of the marginal zones of less-than-clear optics.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

COORDINATION OF HEAD AND EYE POSITION DURING FIXATION

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1. Mathematical equations for the relation between the horizontal compensatory eye rotation and rotation of the head about the vertical axis were derived. The degree of rotation of the two eyes appeared to be different.
2. The distance between the rotation axis of the head and the eye was experimentally determined. It's value appeared to be 80-100 mm.
3. Coordination of the eye and head positions were measured during active head movements, while the subject fixated a stationary target with a variable viewing distance.

THE RELATION BETWEEN COMPENSATORY EYE MOVEMENTS AND ROTATION OF THE HEAD

Whenever we want to fixate an object a rotation of the head is compensated by a rotation of the eyes. A number of studies (Blakemore and Donaghy (1980), Collewijn, Conijn and Tamminga (1982), Biguer and Prablanc (1981)) have pointed out that eye movements should vary as a function of the viewing distance if they are to compensate perfectly for head movements. The reason for this phenomenon is that the axis of horizontal rotation of the head does not coincide with the eye axis.

Let us consider the situation in which a subject has to change fixation from a point A to a point A' (Fig.1), which are situated near the subject. The eye has to rotate through the angle α but the head through the angle θ , if point A is fixated during the rotation of the head through the angle θ , the eye has to make a compensatory rotation through the angle α . This is schematically represented in Fig. 2.

The rotation axis of the eyes lies about 10 cm in front of the head axis. In addition, the eye axes lies about 3 cm lateral to the median plane. Consequently, after rotation of the head to the left, the right eye gets closer to the object and has to perform a greater compensatory movement than the left eye. The ration α/θ for the right eye movement, induced by rotating the head to the left is given by:

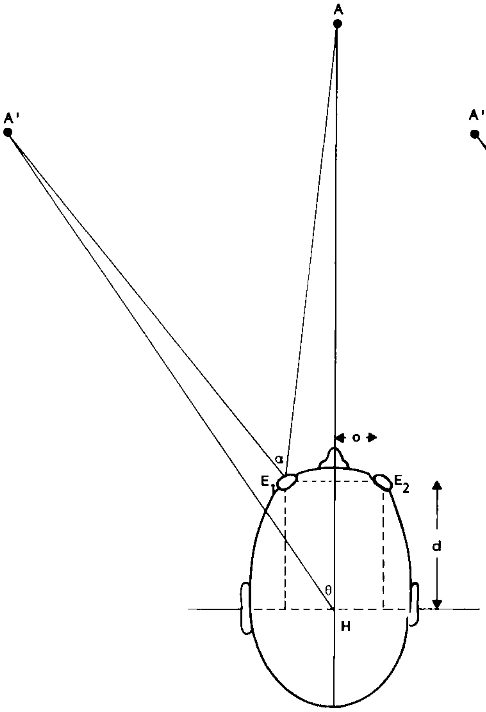
$$\frac{\alpha}{\theta} = \frac{1}{\theta}\left[\text{arc.tan}\left(\frac{o}{L-d}\right) + \text{arc.tan}\left(\frac{L\sin\theta-o}{L\cos\theta-d}\right)\right]$$

and for the left eye

$$\frac{\alpha}{\theta} = \frac{1}{\theta}\left[\text{arc.tan}\left(\frac{L\sin\theta+o}{L\cos\theta-d}\right) - \text{arc.tan}\left(\frac{o}{L-d}\right)\right]$$

These ratios are dependent both on the viewing distance and rotation angle θ.

In Fig. 3 the ratio is shown as a function of θ· The difference between the rotation angle of the right and left eye increases at short distances. The difference is smaller for larger viewing distances. At a viewing distance of 50 cm (corresponding to L= 60 cm) the difference can be neglected for θ no greater than 10^o. In Fig. 4 the ratio α/θ is plotted as a function of the distance between the rotation axis of the head and the fixated object for the right eye, while the direction of head rotation was to the left.



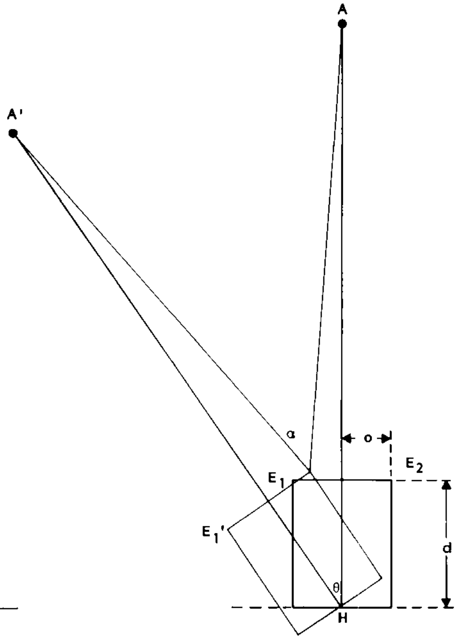


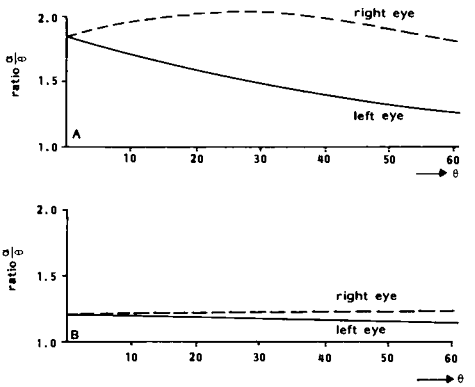
Figure 1
Sketch of the head and an object at close distance in the horizontal plane, when the eye makes a saccade from A to A', followed by a head movement. The compensatory eye movement must be $-\alpha$ and not $-\theta$ for the gaze to remain stationary on target A'.

Figure 2
A schematic diagram of head movement during fixation of stationary target.

DETERMINATION OF THE ROTATION AXIS OF THE HEAD

According to Blakemore and Donaghy (1980) the distance between the rotation axis of the head and that of the eyes amounts to 10 cm. They took for this distance the perpendicular distance between the projected vertical axis of the atlanto-occipital joint and the middle of the line joining the centers of the eyeballs. These measurements were actually made on skulls of man. We determined the rotation axis of the head in a dynamic situation. The vertex was chosen as a reference point. The distance between the rotation axes of the eyes and the vertex was determined as well.

In order to determine the rotation point, 5 LED's were mounted on a bar which was placed on the head in the median plane (Fig.5). On either side of the head a LED was placed opposite the external auditory canal. The intersection of the bar and the frontal plane through the "ear LED's" was called the vertex. The subjects were seated upright on a chair, and were asked to look at a horizontal line drawn on the wall in the front of them at eye level. The subjects had to shake their



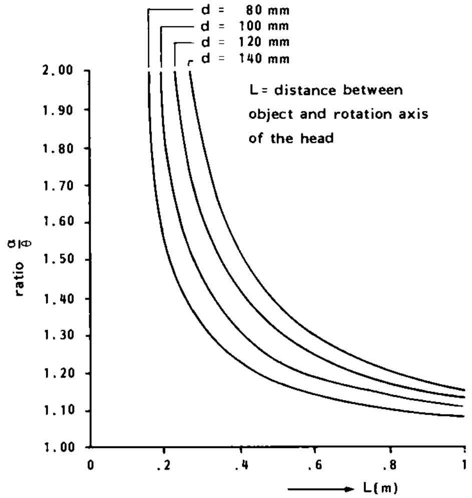


Figure 3
The rotation α/θ as a function of θ for rotation of the head to the left A) L = 20 cm B) L = 60 cm. In both cases o = 3 cm and d = 10 cm.

Figure 4
The ratio α/θ for the compensatory movement of the right eye induced by rotating the head to the left as a function of L. o = 3 cm; d = 8, 10, 12, and 14 cm.

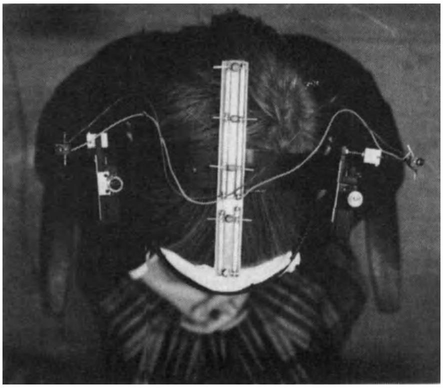


Figure 5
Experimental set-up for determining rotation axis of the head.

heads, keeping the head upright. During the to and fro rotation of their heads photographs were taken in the dark. Such a photograph shows the tracks of the LED's (Fig.6). The rotation point is determined by drawing two lines through the turning points. The place of the vertex can be found by drawing the lines through the turning points of the two LED's which are placed on the line through the outer ear canals (Fig.6).

The tracks show large deviations from circles (Fig.7). These deviations are due to variations of the rotation point. We assume that these variations are due to the fact that the head also makes pitching and rolling movements during the rotational movement about the vertical axis.

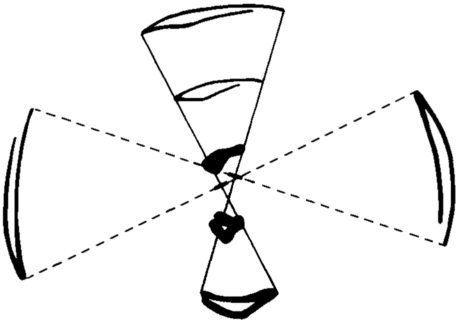


Figure 6
The tracks of the LED's during shaking of the head about the vertical axis and the artificial lines for constructing the rotation point and the vertical place of the vertex.

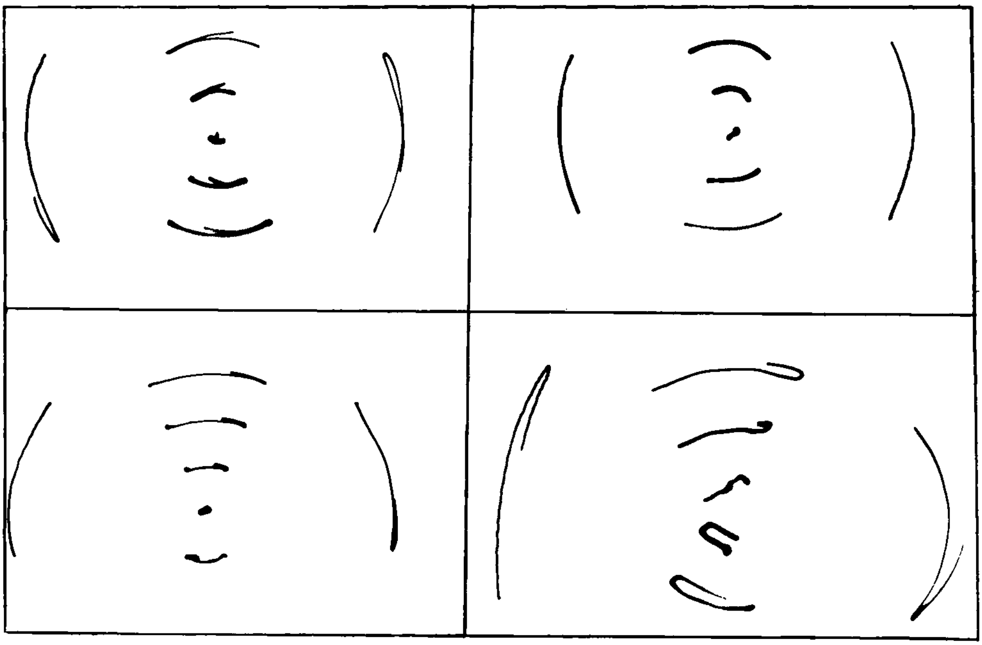


Figure 7
The tracks of the LED's during shaking of the head about the vertical axis. The results of 4 subjects are shown.

If this assumption is correct, the variations of the experimentally determined rotation points would be smaller at the height of the dens. This was checked by placing four LED's at the height of the dens. Two LED's were placed on the line through the outer ear canal and two in the median plane, one in front of and the other behind the head. Figure 8 shows the tracks of these LED's during to and fro rotational movements. The tracks appeared to resemble a circle more closely than in the first experiment and the determinations of the rotation points show less variation.

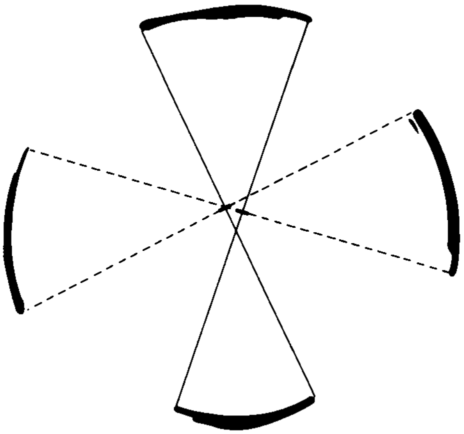


Figure 8
The tracks of the LED's positioned on the height of the dens during shaking of the head about a vertical axis.

When the distance between the vertical line through the outer ear canal, marking the vertex, and the anterior surface of the cornea is determined, the distance between the rotation point of the head and those of the eyes can be calculated. According to Ditchburn ((1973), p 13) the rotation point of the eye is situated 13,8 mm behind the anterior surface of the cornea.

The results of two groups of subjects are presented in Table I. The first group of 12 subjects was investigated with LED's on the height of the vertex only. While the second group of 8 subjects had LED's at the level of the dens as well.

Table I. Distance between the rotation point of the head and the vertex and the associated standard deviation.
Distance between the rotation point of the head and the eyes and the standard deviation.

	ROTATION POINT BEHIND THE VERTEX (in mm)	SD	DISTANCE BETWEEN ROTATION POINT OF THE HEAD AND EYES (in mm)	SD
Group I	14	10	91	10
Group II N = 12 subjects at the level of the vertex	6	9	82	9
At the level of the dens	18	5	93	5

EXPERIMENTAL DETERMINATION OF THE RATIO α/θ

The ratio α/θ as a function of the viewing distance was measured in two cats by Blakemore and Donaghy (1980). They found that the ratio α/θ increased as the viewing distance decreased, but the increase was never quite as high as the theoretical value. We have carried out these measurements for human subjects.

The rotation angle of the head (θ) was determined by means of a potentiometer which was connected to a headband. To measure the angle α an after-image method was used. This method is based on two well-known facts.

1. An after-image povides a retinal "landmark" so that the displacement of an observed scene with respect to the after-image directly reflects retinal image displacement.
2. Although an after-image may fade within a few seconds when seen against a background of constant luminance, it can be viewed for a much longer time against a temporally modulated background field (Ditchburn (1973), pp 44-47).

The experiments ran as follows:
The subject looked at a target which was fixed to him via a bite-board. A photographic flasher behind a mask with vertical lines and a circular hole was placed in front of the subject. The subject looked with his right eye. He had to position the target just underneath the hole in the flashing mask. This location is presented in Fig.2 as A. After the flash the subject turns his head to the left, while fixating the target which moves with him. Then a second flas is given from the same location as the first one. In this situation the subject lookes at A'. The distance between two after-images on the retina reflects the angle α. The distance between the two after-images is determined by looking at a television screen, whose illumination is temporally modulated (modulation frequency 2 Hz). A fixed vertical line is presented on the screen. The subject has to adjust a second line so that the distance between the two lines is equal to the distance between the two after-images. The screen was placed at a fixed distance of about 1,50 m. The method was calibrated as described by Duwaer (1982). The experiments were carried out by two subjects. They were myopics corrected with contact lenses.

The results are presented in Fig. 9. In this figure the ratio α/θ is plotted as a function of the distance L. For the experimental data we have taken for L the viewing distance plus 10 cm. The figures show that the ratio α/θ increases with decreasing viewing distance. For the subject RM the values correspond very well to the theoretical curve. For subject AVL the data points do not fit the theoretical curve as well as the data of subject RM do. The value of d which fits the data is about 11 cm, which is rather high when it is compared with the values found in part II of this study.

In this connection it should be mentioned that d does not represent the distance between the rotation point of the head and the rotation point of the eyes. Because the angle α was determined by marking two points on the retina by flashing point A two times, the apex of the angle (see Fig. 2) is not the rotation axis of the eye but the nodal point. The nodal point, however, lies about 7 mm in front of the rotation point (Ditchburn (1973), p 10).

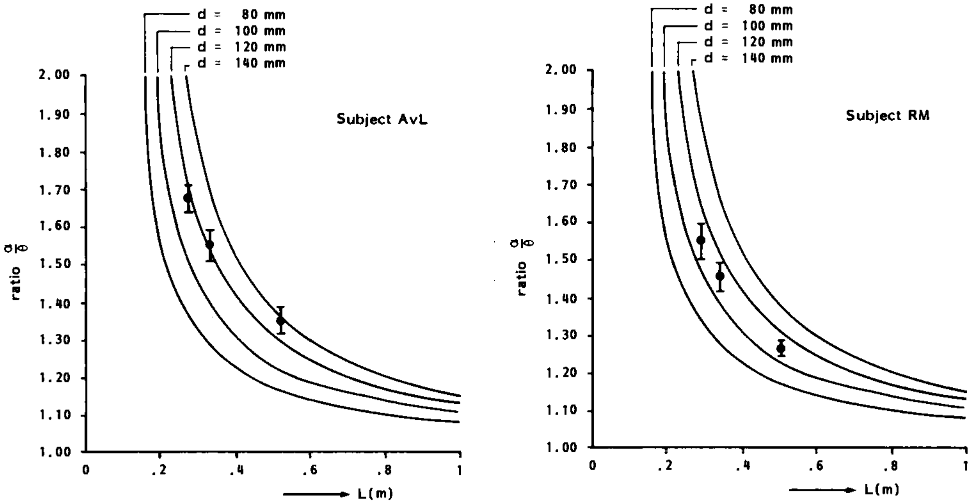


Figure 9
Experimental data of the ratio α/θ for right eye movements induced by rotating the head to the left. Theoretical curves are the same as in Fig. 4.

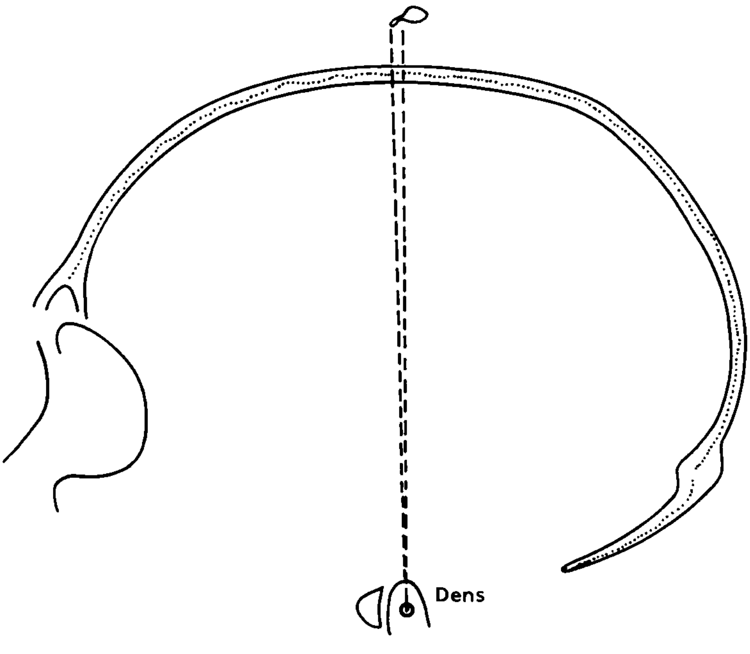


Figure 10
Sketch of the head with its variable rotation axis.

CONCLUSIONS

1. The ratio α/θ for the right eye movement induced by rotating the head to the left is given by

$$\frac{\alpha}{\theta} = \frac{1}{\theta}\left[\text{arc.tan}\ \left(\frac{o}{L-d}\right) + \text{arc.tan}\ \left(\frac{L\sin\theta-o}{L\cos\theta-d}\right)\right]$$

and for the left eye

$$\frac{\alpha}{\theta} = \frac{1}{\theta}\left[\text{arc.tan}\ \left(\frac{L\sin\theta+o}{L\cos\theta-d}\right) - \text{arc.tan}\ \left(\frac{o}{L-d}\right)\right]$$

The ratios α/θ for the two eyes are not equal. The difference between the rotation angle α of the two eyes is not negligeable for short viewing distances.

2. During a shaking movement of the head about the vertical axis, the head makes rolling and pitching movements. This results in a variable rotation axis of the head (see Fig.10).

3. The value of d, i.e. the distances between the rotation axis of the head and the rotation axis of the eyes is about 9 cm for man.

4. The ratio α/θ can be experimentally determined. The results correspond with the theoretical derived relation if for d a value of about 11 cm is chosen.

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EYE MOVEMENTS: From Physiology to Cognition
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ADAPTIVE PHENOMENA RESULTING FROM SURGICAL CORRECTION OF STRABISMUS

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Following strabismic surgery, patients may experience difficulties in locating visually detected objects in space. In most cases of rotation of the pathologically deviated eye (or both eyes as in certain surgical protocols) patients adjust rapidly to the new conditions.

We have investigated sensorimotor changes occurring in the visuo-ocular and visuo-manual systems as a result of surgical correction of strabismus in patients in order to establish relationships between certain syndromes, surgical procedures and surgical effects. Our approach consists of measuring, in each patient, the subjective estimation of the straight-ahead direction as indicated by the eyes and/or the hand, before and after surgical intervention.

Results suggest that two models apply to the behavior of strabismic patients in manual and ocular estimation of the direction of visual targets.

INTRODUCTION

The questions as to how we sense the position of our eyes in their orbits, and how the central nervous system elaborates signals related to body orientations and object positions in space (with respect to the body) are still subjects of exciting discussion. With regard to eye-in-orbit position sense, two main hypotheses have been proposed. According to the first, proposed by Helmholtz in 1867, the brain is informed of the position of the eye in the orbit through a signal derived from the activation of the muscles. This is known as the efferent, outflow, or corollary discharge theory. The second theory predicts that the brain receives signals related to the actual length of ocular muscles as detected by tendon organs and spindle-like stretch receptors. The exact function served by these proprioceptors is not known, but for some authors it is the basis of what is known as the inflow or afferent theory.

Both theories predict that, following strabismic surgery, the patient will have problems related to miscalibration of visual orientation and localisation mechanisms. These problems may become serious in large angle strabismus and in complex surgical procedures in which vertical and horizontal components of the pathological deviation must be corrected. Problems may also arise when the abnormal deviation is corrected in the sound eye, as is done in particular protocols. Yet, in the early hours or days following surgery, patients do not report particular discomfort or sensory motor alterations.

In most cases, then, it seems that sudden modification of eye orientation does not raise major difficulties and patients rapidly adjust to the new condition. Experiments conducted on normal subjects fitted with deviating prisms suggest that adaptive processes develop to restore normal visually guided performance (Stratton, 1897; Held & Gottlieb, 1958; Prablanc, Tzavaras & Jeannerod, 1975). These develop rapidly if the subject is allowed to detect prism-induced errors as in a pointing task executed under visual guidance. When a patient with ocular paresis (Estanol & Lopez-Rios, 1984, Leigh, Newman, Zee & Miller, 1982) attempts to make eye movements or fixate a stationary target while moving the head, or when a subject simply pushes the side of one eye with the finger (Stark & Bridgeman, 1983), he experiences a sensation of instability of the visual world. Visual world instability also develops upon head rotation when a normal subject is fitted with magnifying lenses (Gauthier & Robinson, 1975), or reversing prisms (Gonshor & Melvill-Jones, 1973; Stratton, 1897). In these various situations, disruption of space constancy is attributed to mismatch between retinal image motion and expected eye movement (ocular paresis, eye push), or between head movement and vestibulo-ocular reflex induced eye movements (lens and reversing prism experiments). Following strabismic surgery, one may also expect problems related to loss of space constancy as a result of alteration of the normal relationship between muscle activation and angular deviation due to the weakening or strenghtening of ocular muscles. Such visual world instabilities are not documented. They are probably experienced by some patients. Fortunately, these perceptual alteration problems, as with the sensorimotor alteration resulting from paretic ocular muscles (Kommerell, Olivier & Theopold, 1976; Optican & Robinson, 1980; Miles, 1983) recede gradually through activation of appropriate early-acting adaptative mechanisms.

One may suspect that after strabismic surgery, recalibration of the various visual ocular systems develops as a result of the activation of similar mechanisms leading to genuine adaptation. Yet, it is not known if these adaptative processes are based on the same neural processes as those described above and if they follow a similar time course. Neurological alteration of these mechanisms, or disruption of necessary proprioceptive signals, may also be responsible for the observed failure of the surgical correction in some cases, or the recurrence, after some time, of the abnormal ocular deviation. Signals essential for adaptation and maintenance of proper binocular control may be of proprioceptive origin. Hence, surgical alteration of tendon (resection and recession procedures) and muscle receptors (lengthening loop procedure) may be of importance in the interpretation and outcome of these cases.

To address these questions, we have investigated sensorimotor changes occurring in the visuo-ocular and visuo-manual systems as a result of surgical correction of strabismus in patients in order to establish relationships between certain syndromes, surgical procedures, and surgical effects. Our approach consisted of measuring, in each patient, the subjective estimation of the straight-ahead direction as indicated by the eyes and/or the hand, before and after surgical intervention.

METHODS

The subjective straight-ahead direction for each eye was determined from the angular position of the eye while attempting to fixate an imaginary target placed in the saggital plane. The patient was allowed to practice with a real target shown on a translucent screen positioned 57 centimeters from the eye. Prior to the test, the patient was requested to make a series of alternate rightward and leftward saccadic movements in order to prevent "anchorage" of the fixating eye on the target after its extinction. The subject was seated in front of the screen, the head immobilized by forehead and chin rests. The horizontal component of the movement of both eyes was monitored by DC coupled EOG cupular electrodes. Both eyes were independently calibrated, and the output signals were simultaneously recorded on a DC strip chart recorder and the computer data acquisition system, which included digital disk storage for off-line analysis. The target was a spot of light, one-half degree in diameter, projected onto the back of a translucent target screen. Target displacements for eye movement calibration were produced by a galvanometer-driven mirror inserted along the path of the light beam.

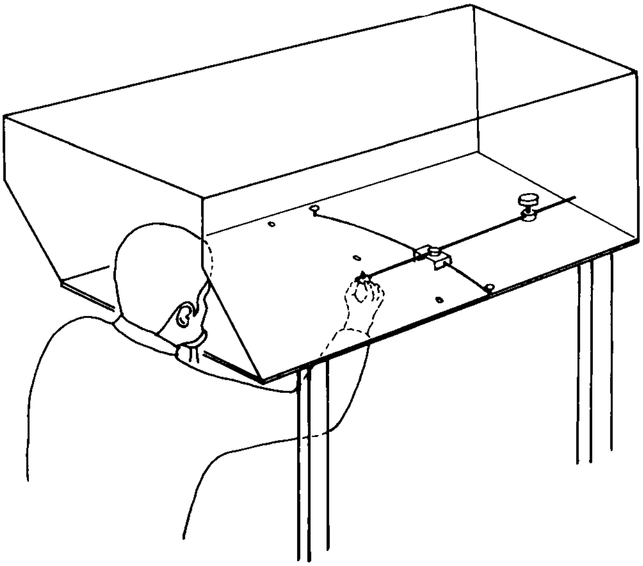

Figure 1: Apparatus designed to monitor target position sensing as indicated by the hand in visual open-loop condition (modified from GAUTHIER, Hofferer, Hoyt & Stark, 1979).

The subjective straight-ahead direction as indicated by the hand was determined by having the patient point at visual targets with the hand in a visual open-loop condition, that is, in total darkness with no vision of the hand (Gauthier, Hofferer, Hoyt & Stark, 1979; Held & Gottlieb, 1958; Prablanc, Tzavaras & Jeannerod, 1975). Three red LEDs were presented on a horizontal board at arm's length (45 centimeters). One diode was placed in the midline with the two others ten degrees on either side. The targets were randomly illuminated and the patient indicated the perceived position of the target by moving a thin knob made to slide along a rod placed below the board as shown in Fig. 1. The indicated position was recorded by means of a potentiometer whose output was calibrated for each target position, then stored on a microcomputer (IMS 8000). Alternatively, "pointing maps" were constructed by asking the patient to point directly at the target, from under the board, with a colored marker. This procedure allowed us to evaluate the dispersion in both anteroposterior and lateral directions while the regular procedure provided only lateral pointing error.

Patients ranging in age from nine to fifty years participated in the eye and hand tests. They were from the Ophthalmology Department of the Hopital Nord in Marseilles. Each patient was tested once during the preoperative day, once early in the postoperative day, and once or twice in the following three to four weeks. The subjective eye position test was executed before the hand position test.

RESULTS

Figure 2 illustrates the pre-operative performance of a right-eye esotropic patient in the task requiring to direct gaze at an imaginary target in the saggital plane. Right and left portions of the record correspond to calibration sequences. The left eye fixated the target while a patch covered the right eye. When the target was extinguished, the patient was requested to make large horizontal saccades and then direct his gaze toward the position of the previously shown target. The patient was requested to fixate the target as soon as it reappeared on the screen. The amplitude of the saccade necessary to recapture the target was the measure of error in the estimation of the straight ahead direction. Ten to twenty similar trials were averaged for each eye sequentially.

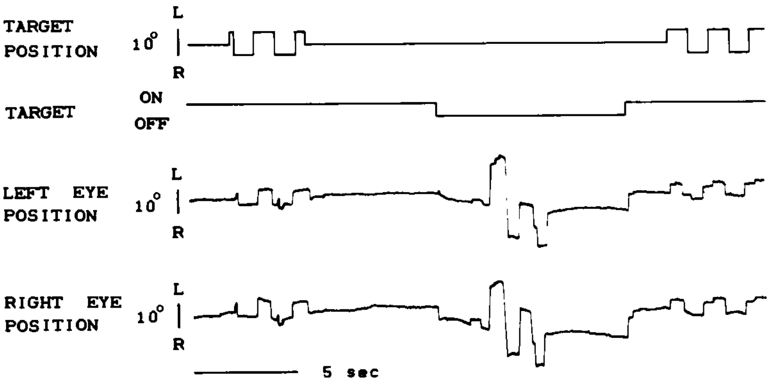

Figure 2: Sensing of straight ahead direction as indicated by the eye. From top to bottom: recordings of horizontal target position, target state, left and right eye horizontal position. Left and right positions of records correspond to 10 degree peak-to-peak calibrations. The right eye was patched. During the target extinction period, the patient was told to move his eyes right and left to prevent anchoring of gaze onto the remembered position of the target. When the target was re-illuminated, the patient recaptured the fixation target with a saccade whose amplitude is a measure of the error of appreciation of straight ahead direction.

Pointing maps (see methods) illustrating the open-loop performance of a normal subject (upper) and a right-eye esotropic patient before surgery are shown in Fig. 3. The actual positions of the targets are designated by black squares. The pointing error for each eye was calculated as the average over six pointings for each target. The diversity of the syndromes and the surgical protocols did not allow us to construct a detailed classification of the data from the 24 tested patients. However, they were separated into two classes according to the exo, or eso nature of their deviation. Right and left eye strabismus cases were pooled, under the assumption that they are mirror-images of each other. The results were similarly diversified and not all patients could be definitively classed into limited categories. However, 16 of the patients could be divided into two groups, defined by characteristics such as direction of the strabismus, and direction of the pointing error with the corrected or incorrected eye fixating. The remaining 8 patients could not be included in either class.

The first class, composed of 11 patients (five right-eye eso, three left-eye eso, one right-eye exo, two left-eye exo), produced similar errors in gaze and hand pointing. Before and after surgery, these patients made no errors in either eye or hand tests when the sound eye was used to fixate. When using the strabismic eye to position gaze before surgery, they made an error of 40% to 70% of strabismic angle in the direction of the pathological deviation. In the pointing task these patients demonstrated a systematic error of 25% to 60% of strabismic error, but in the direction opposite to the pathological deviation. After surgery, all these patients pointed in the vicinity, though with large dispersion, of the target with either eye fixating. The upper left part of Fig. 4 summarizes the average performance of the patients in this class.

Five patients (3 right-eye eso, 1 left-eye eso, 1 right-eye exo) formed a second, fairly coherent class. They performed in a similar manner in both eye and hand tests. Two had alternating strabismus with better than 20/50 visual acuity.

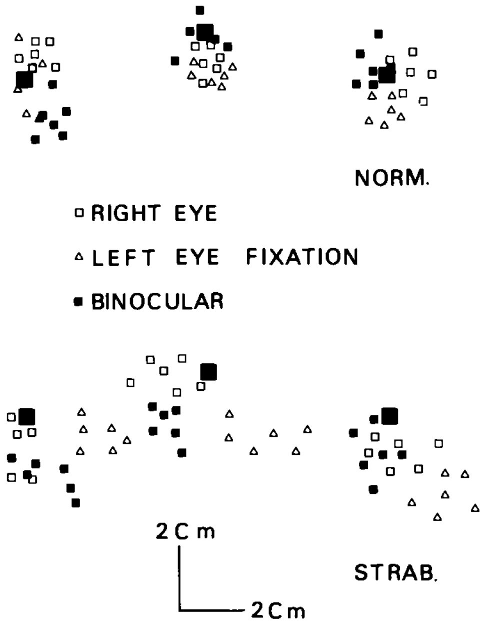

Figure 3: Sensing of visual target position as indicated by the hand in the visual open-loop condition. Typical pointing charts in normal subject (top) and in a strabismic patient (bottom).

Before surgery, the five patients made no errors, but there was large inter-trial dispersion in the gaze direction task. After surgery, they made large errors in the direction of strabismus when using the operated eye. The lower left part of Fig. 4 summarizes the performance of this class in the hand pointing task. It shows that preoperative pointing is normal (R1, L1) with both eyes. After surgery, fixation with the non-operated eye produced no error (L3) while fixation with the operated eye produced large errors (R3) in the direction of the previous deviation. The individual error was 20% to 50% of the strabismic angle.

Particular attention has been devoted to the data gathered from the patients of these two classes over a one to two month post-operative period. The finding in all but one patient was that they either refined their performance (first class) or progressively recovered close to normal visual motor performance (second class). Adaptation to surgical deviation took place within a few days, or at most, two to three weeks indicating proper recalibration of the perceptual and motor mechanisms responsible for sensing eye position and locating objects in space.

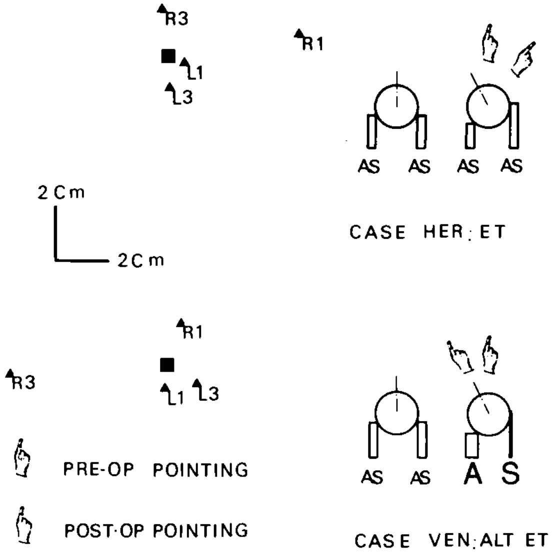

Figure 4: Data and simple models for strabismus. Based on our data, two models may be proposed. A and S symbolize motor activation and muscle stretch, respectively.

a - (upper): pathological deviation appears to result from mechanical alteration of the eye resting position,

b - (lower): deviation due to spontaneous hyperactivation of one (or more) muscle.

From our preliminary data it appears that at least two models apply to the behavior of strabismic patients in directional tasks such as described above. It may be that alternating strabismic patients with close-to-normal vision constitute a definite group, different from monocular suppressing patients.

The patients from the first group behaved as if the strabismic deviation was caused by an essentially mechanical factor affecting the resting position of the eye, as represented in the upper right drawing of Fig. 4. When the normal eye looks straight ahead, the muscles of both eyes are in an equilibrium position and the direction of gaze is sensed correctly. When the strabismic eye is used to fixate the same target, an appropriate activation is addressed to the muscles to compensate the pathological deviation. When this position is attained, the sound eye is directed to a position equal, but opposite to the strabismic deviation. It is this compensated position which is sensed as straight ahead. After surgical rotation of this eye in the orbit, the straight ahead direction is now obtained in the equilibrium position, and this direction is correctly sensed.

The patients from the second group behaved as if the strabismic deviation was caused by inappropriate nervous activation affecting permanently, and more or less constantly one muscle, as shown in the lower drawing of the Fig. 4. When the normal eye looks straight ahead, the other eye is deviated as a result of the hyperactivation of the affected muscle. (Alternatively, the strabismic deviation could also result from the hyperactivation of homonymous muscles in both eyes). When the patient fixates a straight ahead target, an activation is addressed to the muscle opposite the one affected, in order to compensate its spontaneously activity. The resultant equilibrum activity is sensed as the correct straight ahead direction. Immediately after surgery, the actual straight ahead direction is sensed as that corresponding to the previous resting position of the eye and the patients tend to make a pointing error almost equal to the original strabismic deviation. Implicit in this model is the assumption that position sense is derived either from inflow information and/or from outflow signals which include the hyperactivity.

CONCLUSION

Our data do not allow to distinguish between afferent and efferent information in eye position sensing. They also do not provide details on the adaptative recalibration after surgery. However, based on preliminary correlative analysis of surgical effects, time course of adaptive recovery and surgical procedure, it is likely that, as recognized by Steinbach & Smith (1981), tendon organs are necessary for ocular position sensing (as in skeletal muscles: Matthews, 1982). Muscle receptors are probably also necessary to provide inflow information, matching efferent copy, a key to the maintainance or restoration of appropriate ocular system perception and motor control. We also note that our interpretation of the difference in patient behaviour differs from that proposed by Mann, Hein & Diamond (1979), which attributes the difference to the way in which visual space is represented in constant and alternating suppressor patients.

Analysis is still in progress to fit other patients into the two main classes identified thus far, or to develop additional classes based on other criteria. In particular, we are attempting to correlate the effects of surgery as demonstrated by eye and hand pointing tasks with the nature of the strabismus, visual acuity of the deviated eye and surgical correction, criteria such as the action on the sound eye vs. that on the deviated eye, tendon resection and/or recession or muscle lengthening.

Parts of these data were presented at the Conference on Oculomotor System Plasticity, Asilomar, September 1985.

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EYE MOVEMENTS: From Physiology to Cognition
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MACRO SQUARE WAVE JERKS INDUCED BY BINOCULAR FIXATION ATTEMPTS

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Quantitative eye movement recordings in a patient with suspected multiple sclerosis who had alternating esotropia, horizontal nystagmus, downbeat nystagmus, and saccadic dysmetria, showed occasional macro square wave jerk intrusions and oscillations in the fixating eye during spontaneous monocular fixation, and binocular macro square wave jerk oscillations during the effort to fuse.

INTRODUCTION

Visual fixation may be interrupted by either sporadic eye movements or by sustained oscillations. The latter include the various forms of nystagmus and saccadic oscillations. In all forms of true nystagmus, a slow eye movement (SEM) is responsible for the genesis and continuation of the oscillation. The cause of the SEM is one of the features which differentiate the various types of nystagmus. Fast eye movements (saccades), if they are present, have a corrective function and do not constitute the basic instability. Saccadic oscillations are inappropriate saccades which occur repetitively, causing ocular oscillation. They include macro square wave jerks (MSWJs), macro saccadic oscillations, ocular flutter, voluntary "nystagmus" and opsoclonus. Sporadic disturbances (or saccadic intrusions) are saccades which occur singly or in small groups. They include square wave jerks, saccadic pulses, and double saccadic pulses (Dell'Osso, 1980).

Macro square wave jerks are horizontal spontaneous saccades which conjugately move the eyes from the object of fixation to some point in space lateral to that object. After a brief latency (approximately 80 ms) a non visually mediated corrective saccade returns the eyes to the target. MSWJs have been reported to occur in bursts during binocular fixation at a distance or following a voluntary refixation, and to be suppressed by monocular fixation (Alpert, Coats & Perusquia, 1975; Dell'Osso, Troost & Daroff, 1975; Dell'Osso, Abel & Daroff, 1977).

We report a patient with nystagmus, alternating esotropia, and saccadic overshoot dysmetria, in whom occasional monocular MSWJ occur sporadically as intrusions, and continuously as an oscillation in the fixating eye during spontaneous monocular fixation, and binocular MSWJ oscillations occur during binocular fixation attempts.

CASE REPORT

A 35-year-old aircraft pilot was first admitted to the hospital in January 1982 for sudden onset of oscillopsia and diplopia which gradually became more noticeable and constant. On examination he was found, at that time, to have upper limb dysmetria.

Clinical examination of extraocular movements revealed an alternating esotropia of 15 prism diopters. The fixating eye showed horizontal jerk nystagmus in primary position which increased in amplitude on looking laterally. There was nystagmus on upgaze and downgaze. Visual acuity was 20/20 in each eye with normal colour perception. The pupils reacted normally to light and to close stimulations. Visual fields were full. Fundoscopic examination was normal. Except for abnormal eye movements, and upper limb dysmetria, the neurological examination was normal. Lumbar puncture demonstrated 2 WBC/mm3 (100% lymphocytes), normal glucose and protein of 54 mg/dl with normal gamma globulin fraction and no oligoclonal bands by immunoelectrophoresis. CT scan, auditory evoked potentials, EEG, ECG and blink reflex were normal. He began receiving steroid therapy with worsening of diplopia and oscillopsia. He was discharged from the hospital with a diagnosis of suspected multiple sclerosis. Repeated neurological examinations over the next 3 years revealed only abnormal eye movements.

When referred to the Neuroloy Department, Sassari University, in February 1985, the patient showed normal neurological examination except for eye movements. He had an alternating esotropia of 15 prism diopters. Looking straight ahead the fixating eye, usually the right eye, showed a downbeat nystagmus while the esotropic eye showed a horizontal jerk nystagmus. He had uncrossed diplopia and complained of oscillopsia in both images. On lateral gaze a jerk nystagmus, with fast phase beating in the direction of the fixating eye, was present as the fixating eye moved from the midline towards abduction; its amplitude increased as that eye moved into full abduction, where real image oscillopsia, and, concomitantly, visual acuity, worsened. Nystagmus was absent when the fixating eye was in adduction. Hence he spontaneously fixated with the right eye in the left gaze and vice versa with the left eye in the right gaze. In the beginning the patient adjusted to his visual disability, using either eye for watching television or for driving a car. Later on he learned how to distinguish the "real" image from the double one (which always appeared to be in motion), so that, for instance he could drive a car with binocular viewing. By exercise he also learned, while looking at a still target, how to decrease the separation of the images. During these attempts to restore single binocular vision he always manifested leftward large-amplitude binocular horizontal oscillations, having the clinical appearance of MSWJs. The oscillations persisted throughout the attempts of binocular fixation. Such a phenomenon was never seen during spontaneous monocular viewing or after the correction of the esotropia by a prism. He reported that during the MSWJs the double and the "real" image, which became closer oscillated, with their separation changing continuously. To induce MSWJ oscillations he had to reduce the esotropia, and slightly adduce the fixating eye. He could maintain the oscillations for several seconds, during which his facial expression reflected signs of effort and concentration. No fluttering of the lids occurred. MSWJs also occurred during gaze deviations at less than 15°. Repeated oculographic recordings (two months later) still showed a similar oculomotor disturbance.

METHODS

Horizontal eye movements were recorded using infrared oculography. A vertical EOG recording was used to detect blinks. Eye movements were electronically differentiated and both position and velocity traces were recorded on a Beckman type R 612 Dynograph. The entire system bandwidth (position and velocity) was DC-30 hz. The patient was seated with the head stabilized in the mid-position by chin, forehead, and occipital supports at the center of a 5 ft radius arc containing red light-emitting diodes. Eye position was monitored with targets at the mid-position and at 5°, 10°, and 20° to either side of mid-position. Calibration was accomplished monocularly for each eye (other eye covered). In this way we could align exactly the tracings for each eye on the target and then, when the cover was removed, detect even the smallest tropias during binocular viewing. The term "binocular viewing" is used in this paper to describe the condition where both eyes were allowed to see, and it does not imply "binocular fixation", a term that we used to designate foveation of the target by both eyes.

RESULTS

Figure 1 illustrates the presence of alternate shifts between right and left esotropia during binocular viewing of a distant target in primary position. Initially the patient was fixating with the right eye while the left eye was esotropic and had left jerk nystagmus. As the left eye moved to the primary position, he assumed fixation with the left eye and the right eye became esotropic and exhibited a right jerk nystagmus.

Figure 2 shows bursts of MSWJs which appeared when the patient was instructed to attempt to fixate a target in primary position binocularly. Initially he was fixating with the left eye and the right eye was in an esotropic position. As he started his attempt to fixate binocularly (left arrows) binocular bursts of leftward MSWJs occurred after a rightward saccade. The oculographic tracings show that the onset of the MSWJs coincided with the reduction of the right eye esotropia while the left eye moved slightly from the straight position to the right (i.e. reduction of strabismus). During the oscillations a conjugate wandering of the right eye was evident and the lines of sight between MSWJs changed continuously. As he was instructed to stop the effort of fixating binocularly (right arrows) the left eye moved to the straight position, the right eye drifted back to the previous esotropia and the MSWJs disappeared. Similar findings were obtained with the right eye fixating.

Figure 3 shows both sporadic and oscillatory leftward MSWJs of small amplitude that occurred occasionally only in the fixating eye. They have been observed in both primary position and lateral gaze.

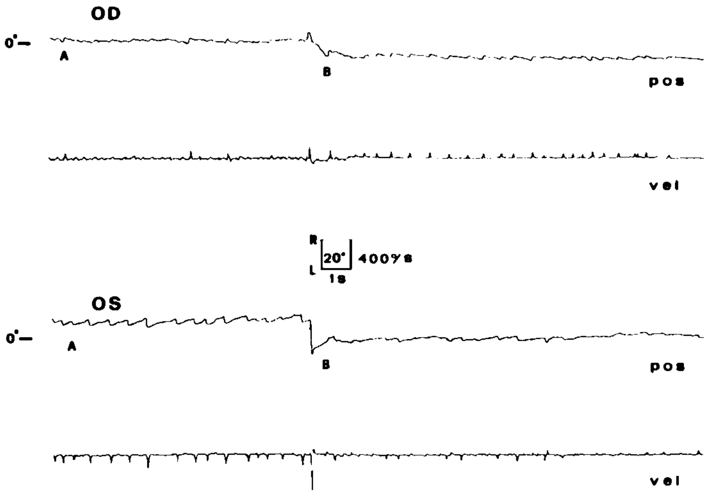

Fig. 1 Alternating shift between right and left esotropia. Initially (A) the patient was fixating with the right eye (OD) while the left eye (OS) was esotropic. As OS moved to the primary position (B) it assumed fixation and OD became esotropic. Primary position is indicated by the horizontal line labeled 0°. Eye movement directions right (R) and left (L) are indicated. Pos = position, Vel = velocity. Same symbols apply to all other figures.

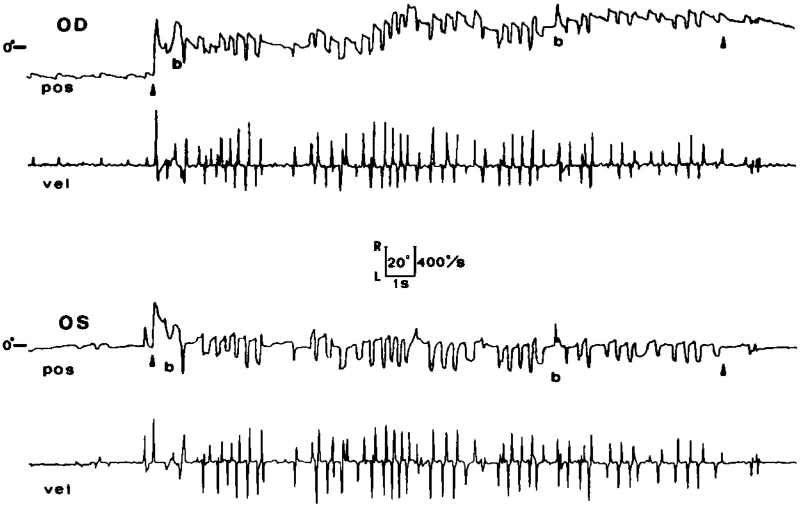

Fig. 2 Binocular position and velocity recordings of bursts of MSWJs appearing on command during binocular fixation attempts (between left and right arrows). The oscillations consist of a leftward saccade followed, after a brief latency, by a rightward saccade.

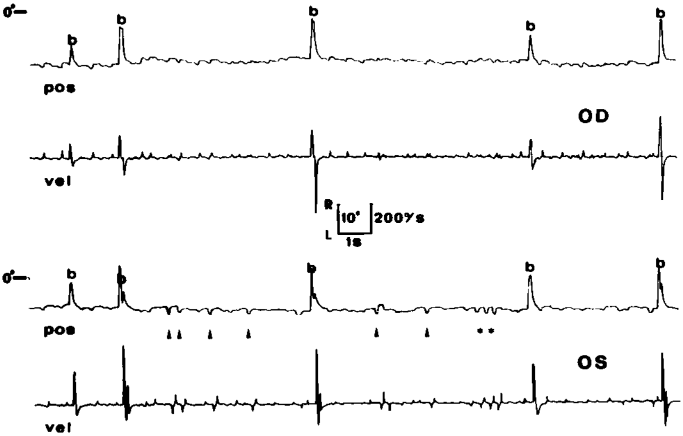

Fig. 3 MSWJ intrusions (▲) and a MSWJ oscillation (**) in the left eye fixating.

Figure 4 documents the absence of nystagmus in the right eye fixating when that eye was adducted and the left eye covered. As the right eye moved to the right, a jerk nystagmus beating in the direction of the fixating eye appeared, and its intensity

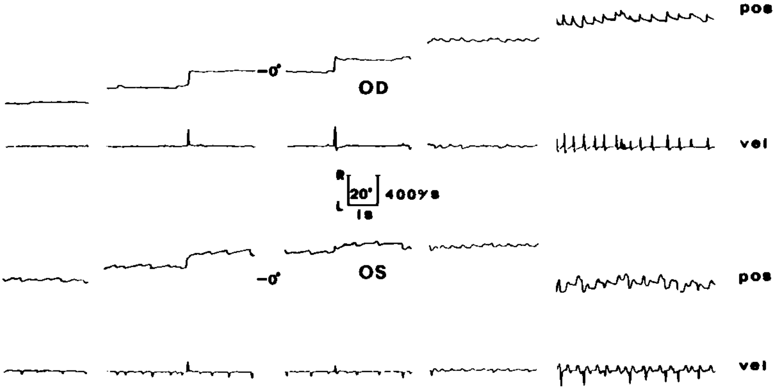

Fig. 4 Variations of nystagmus with OD fixation gaze angle. The OD slow phases consist of exponentially decreasing velocity profiles. Fast phases exhibit dynamic overshoot.

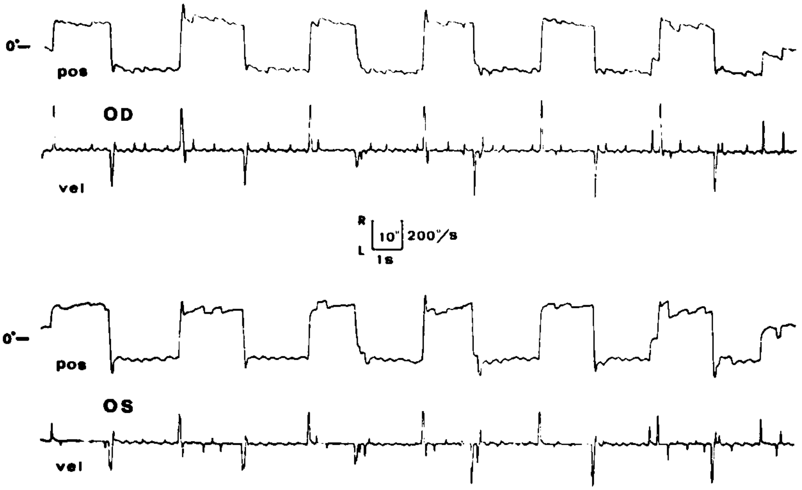

Fig. 5 Horizontal saccadic dysmetria.

(amplitude x frequency) increased with increasing abduction. Similar findings were obtained from the fixating left eye with the right eye covered.

Figure 5 shows that refixation horizontal saccadic eye movements were dysmetric. The initial saccade commonly overshot the position of the target and a corrective saccade was required to bring the eyes back to the target.

DISCUSSION

The patient demonstrated a number of eye-movement system abnormalities: 1) alternating esotropia, 2) monocular MSWJ intrusions and oscillations in the fixating eye during spontaneous monocular fixation, 3) binocular MSWJ oscillations during voluntary binocular fixation attempts, 4) horizontal and downbeat nystagmus.

MSWJs usually occur in bursts and have been classified only as oscillation, as distinct from saccadic intrusions such as square wave jerks, saccadic pulses, and double saccadic pulses (Daroff, 1977). However as Abel and coworkers pointed out (Abel, Traccis, Dell'Osso, Daroff & Troost, 1984), such a separation is artificial: all saccadic fixation instabilities can occur sporadically as an intrusion and continously as an oscillation. Our patient supports this view. Two basic patterns were seen. In one (MSWJ intrusion) single MSWJs appeared only in the fixating eye during spontaneous binocular viewing conditions. In the second pattern (MSWJ oscillation) bursts of binocular horizontal MSWJs appeared as the patient attempted to voluntarily fixate a target binocularly.

MSWJs are usually induced by visually guided attempts of fixation or smooth pursuit and can occur in the dark or with the eyes closed only during attempts to look at an imagined object (Dell'Osso et al., 1975; Alpert et al., 1975). Dell'Osso et al. reported a variety of MSWJs ("inverse latent") which are present with binocular fixation at a distance but stop when either eye was closed (Dell'Osso et al., 1977). Our patient showed sporadic small-amplitude MSWJs in the fixating eye during spontaneous binocular viewing. On command he could induce large amplitude binocular MSWJs while looking at a still visual image during a distinct effort to attempt to restore single binocular vision. He was not able to induce the phenomenon if the esotropia was corrected by a prism. Thus, the MSWJs manifested an attribute that has not been previously reported: present during monocular fixation only in the fixating eye and binocularly during binocular fixation attempts at a still image, they stopped with both eyes aligned on target.

The pathogenesis of the MSWJs is not obvious but may represent an instability of the saccadic pulse generator which lies in the paramedian pontine reticular formation (PPRF). Three types of brainstem units are related to saccadic eye movements: pontine burst units, pontine pause units and tonic neurons. The burst neurons are usually silent but fire at high rate (600 to 1000 spikes per second) just before the initiation of a saccade. They project to the ipsilateral abducens nucleus, where two types of neurons lie: abducens motor neurons, with axons innervating the lateral rectus muscle and abducens internuclear neurons which, via the controlateral medial longitudinal fasciculus, project to the controlateral medial rectus motoneurons (Baker & Higstein, 1975; Steiger & Buttner-Ennever, 1978). Pause neurons discharge continuously except immediately prior to the saccade. Usually they pause for the duration of the saccade. During fixation, pause cells prevent burst cells, which might be inherently unstable, from creating extraneous saccadic pulses and unwanted ocular oscillations. Saccadic oscillations can then occur for abnormal control of saccadic burst neurons by the pause cells (Zee & Robinson, 1979; Daroff, 1981). This could result from abnormalities of the pause neurons themselves or from abnormalities of the controlling signals arising from other centres, for example the cerebellum . It was, in fact, postulated that the cerebellum modulates saccadic gain (Optican & Robinson, 1980). In our patient the presence of a cerebellar disorder suggested by downbeat nystagmus, horizontal nystagmus as well as saccadic dysmetria, supports the key role of cerebellar pathology in generating saccadic oscillations.

Our patient complained of diplopia, and oscillopsia as do most patients with acquired nystagmus. The nystagmus was constant in the esotropic eye (as well as the oscillopsia of the double image), and appeared in the other (fixating) eye as soon as it moved into abduction. At that moment the esotropic eye became the fixating one and its nystagmus disappeared. Thus, the sight strategy adopted by the patient to improve his visual acuity was to fixate with the right eye in the left gaze and with the left eye in right gaze.

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EYE MOVEMENTS: From Physiology to Cognition
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GAZE CONTROL IN MAN: EVIDENCE FOR VESTIBULO-OCULAR REFLEX INHIBITION DURING GOAL DIRECTED SACCADIC EYE MOVEMENTS

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Human subjects were required to track a visual target stepping from the center to a peripheral position while their head was either fixed or passively rotated in the targets' horizontal plane. Moving the head toward the target resulted in a significantly higher saccadic gaze velocity (both peak and mean velocities) than under head fixed, while gaze shift accuracy remained unchanged. These results, together with the observation of an eye movement exactly compensating for head rotation just before and after the saccade, suggest an inhibition of the vestibulo-ocular reflex (VOR) within saccadic response duration.

INTRODUCTION

For many animals, the most accurate and reliable source of information about the outer world used in their spatially oriented behavior derives from the visual system. This requires an efficient ocular motility performed by specialized oculomotor subsystems : pursuit system, optokinetic reflex, cervico-ocular reflex, vestibulo-ocular reflex (VOR) and saccadic system. We will focus on the two latter ones. Stabilization of retinal signals when the animal is moving is mainly achieved by the VOR ; instead the saccadic system is responsible for scanning movements across the animal's visual field to bring the image of an object of interest on the central part of the retina for fine discrimination.

In natural orienting behavior toward an attractive stimulus, the combined saccadic eye movement and head rotation (which is the actual stimulus for VOR) raise the problem of how these two antagonistic eye movements interact to bring accurately the gaze (or visual axis) onto the target position. The first appealing response to this problem of eye-head coordination was given by Bizzi's group (Morasso, Bizzi and Dichgans (1973) ; Dichgans, Bizzi, Morasso and Tagliasco (1974) ; Bizzi (1975)). They showed that when monkeys could use both their eyes and head to orient their gaze toward a visual stimulus, the shape of gaze shift was the same as when their head was restrained. In other words, the velocity and dynamics of gaze shifts were similar in both conditions. The authors concluded that the VOR induced by head rotation exactly cancels the contribution of head displacement both during the saccadic eye movement, and after the saccade, gaze being kept on target through both fixation and VOR, as the head is continuing to move. This theory implied a VOR operating at a constant unity gain, and subtracting the head displacement from the oculomotor command in a head coordinate system. It was supported by additional experimental data obtained in rabbit (Collewijn (1977)), in cat (Blakemore and Donaghy (1980) ; Guitton, Douglas and Volle (1984)) and in man (Barnes (1979)).

However, recent studies in the cat have shown that gaze velocity is faster when the head is allowed to move than when it is fixed (Haddad and Robinson (1977) ; Roucoux, Guitton and Crommelinck (1980) ; Fuller, Maldonado and Schlag (1983)). These authors have suggested that VOR gain is reduced during the saccadic gaze shift so that VOR does not exactly compensate for head movement. This hypothesis of a partial additivity between VOR and saccadic ocular command has been recently put forward also in man in two studies (Jürgens, Becker, Rieger and Widderich (1981b) ; Robinson and Zee (1981)). In addition to this VOR inhibition, a local feedback loop providing an estimate of absolute gaze position has been imagined within the saccadic system to stop its phasic activity once the gaze reached its goal (Roucoux et al. (1980); Robinson and Zee (1981) ; Fuller et al. (1983)).

These contradictory results have led us to investigate the dynamics of gaze shifts made by human subjects toward visual targets either with their head fixed or passively rotated. The goal of the study is to know whether the same mechanisms, according to a partial additivity hypothesis of gaze control, still operate during saccadic gaze shifts combined with a passive head rotation. In the affirmative alternative, gaze behavior would be expected to depart from normal gaze shifts with the head fixed: gaze velocity should be greater when the head is directed toward the target (i.e. in the same direction as the saccadic eye movement) and less when the head is rotated in the opposite direction. Moreover, the above hypothesis of a central computation of the gaze position signal should be discussed on the basis of gaze accuracy measurements performed under high head velocities.

APPARATUS AND METHODS

Subjects were sitting in a darkened room in front of a horizontal semicircular screen whose radius of curvature corresponded to the distance between the screen and the axis of rotation of the head (1.2m). Peripheral visual targets (red light emitting diodes) were located at 30 and 20 degrees right and left from a central target, along a horizontal line of the screen. In one experimental session, a torque-motor was used to drive the subjects' head in a horizontal plane during their saccadic ocular response. A helmet and a bite-board rigidly linked the head to the servo-driven torque-motor. The measured dead zone between head position command and actual head position did not exceed one degree. The entire experiment was controlled by computer: rotation of the torque-motor controlling head position, random selection of target position, and sampling of eye and head position signals at 1000 Hz. Head position was derived from a potentiometer fixed on the helmet rotation axis and eye position signal from an electro-oculographic (EOG) technique (with analog filter of 80 Hz cut-off frequency and an automatic counter-drift device). After an off-line linearisation of the EOG signal, absolute gaze position was reconstructed by adding the two signals sampled by the computer: eye position in the orbit and head position.

In the two following experimental sessions every trial consisted in a target step from the center to a randomly selected peripheral position, followed by another target step back to the center. Four targets were presented 8 times at 20 and 30 deg from the center on each side, in a random order. Four subjects (2 males, 2 females) one wearing corrective glasses, but none with known vestibular deficits, were used in the study. They were instructed to track the target when it jumped from the central point to a peripheral one, irrespective of the imposed head movement, when it occurred.

In the first experimental session, the head was immobilized in a straight ahead position, while in the second one a passive rotation of the head was applied during subjects' saccadic response to the peripheral target. In the second session, the head was rotated toward the peripheral target ("target ipsi" condition) on half the trials and it was rotated toward the opposite direction ("target contra" condition) on the remaining trials. In order to quantify interactions between VOR and saccades, a constant angular head velocity (200 deg/s) had to be maintained at least during the whole saccadic response. Head rotation started from a 40 deg eccentric position (the eye fixating the center and thus starting from a 40 deg eccentric position in the orbit) and ended either at the symmetrical opposite side for the "target ipsi" condition or at a 10 deg opposite position for the "target contra" condition. The latter asymmetry allowed subjects to fixate the more peripheral target until the end of the trial by keeping the eye within its physiological range (see fig. 1). To avoid any kind of adaptation, the size (20 and 30 deg) and the direction of target steps (ipsilateral or contralateral) with respect to the direction of head motion were randomly mixed during this second session. Care was also taken to avoid effects of fatigue by restricting the total number of trials to 32 in both sessions.

In the "target ipsi" condition, gaze orienting behavior predicted from the partial additivity hypothesis corresponds to a reduced saccadic duration and an increased gaze velocity with respect to the head fixed behavior. The same hypothesis predicts exactly the opposite effects in the "target contra" condition.

RESULTS

The three original responses shown in Figure 1 are representative of the general behavior of the four subjects. From top to bottom are represented the oculomotor responses to a 30 deg target step in "target ipsi", "target contra" and "head fixed" conditions. In both head driven trials ("ipsi" and "contra") slow eye movement compensates nearly for all head movement: it keeps gaze on the central position before the saccadic response, and on the peripheral target position after it. The comparison of gaze trajectories between "target ipsi" and "head fixed" conditions reveals an obvious difference in the shape of gaze shifts. This detail is even more striking on gaze velocity profiles: when head and target move in the same direction maximum gaze velocity is greater and saccade duration is shorter than in "head fixed" condition. In contrast, no clear differences appear in the dynamics of gaze shifts (either peak gaze velocity or saccade duration) between "target contra" and "head fixed" conditions. As it was difficult to rely on accurate measurement of saccade duration (as seen in "target ipsi" response of Fig 1), maximum gaze velocity seemed to be more reliable than mean gaze velocity and was preferentially used to quantify the interaction between VOR and saccadic ocular command. The averaged results of this computation are summarized in Figure 2. Three main points are worth noting :
a) a constant increase of maximum gaze velocity across all subjects and target step sizes ($p<0.01$) can be observed when the head is rotated toward the target position ("target ipsi" condition) with respect to "head fixed" condition.
b) maximum gaze velocity is not significantly different between "target contra" and "head fixed" conditions (except for subject FM at 30 deg, $t_{14}=5.0$, $p<0.01$).
c) the differences of maximum gaze velocity between "target ipsi" and "head fixed" conditions are not affected by the size of target steps (except for subject MI, $t_{14}=2.96$, $p<0.02$).

The quantitative observations as well as the previous qualitative ones do not support the full additivity hypothesis. Instead the increase of maximum gaze velocity (as well as mean gaze velocity not shown here) observed when head and target move in the same direction favors the hypothesis of VOR gain inhibition during the saccade. A last observation can be made from Figure 2. Although all subjects seem to exhibit roughly the same behavior with respect to experimental conditions and target eccentricities, there is a large inter-subject variability in maximum gaze velocity and in their differences with respect to experimental conditions. This observation could also be made for the mean gaze velocity and suggests that the percentage of VOR inhibition during the saccade is not the same for all subjects.

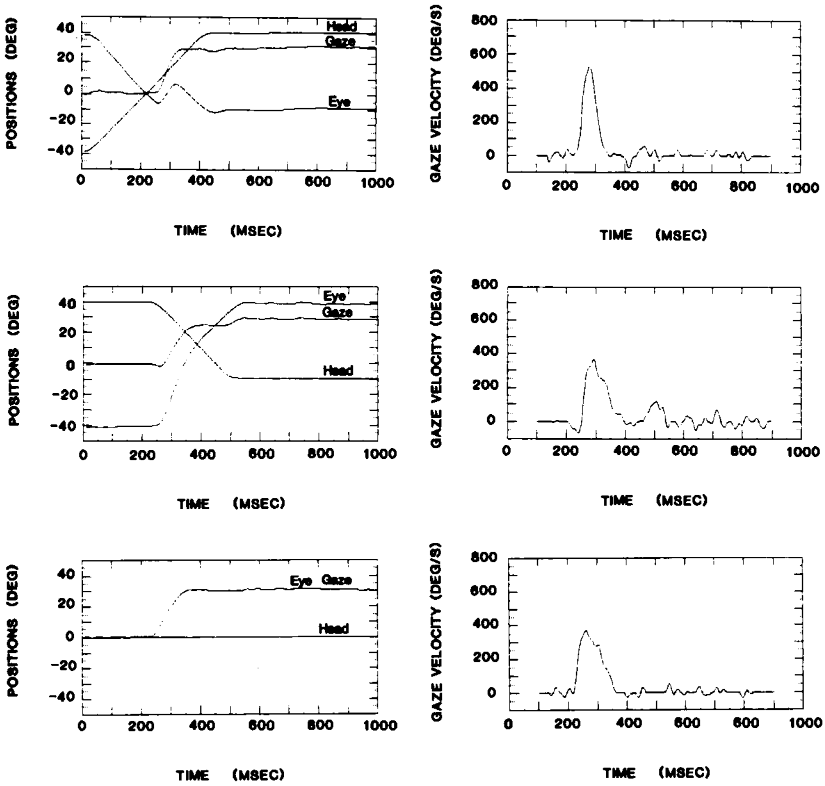

Figure 1
Individual responses from one subject (GB) to the same 30 deg target step on the right side, in the three experimental conditions: "target ipsi", "target contra" and "head fixed" (from top to bottom). Gaze position was computed merely by adding signals of eye position (linearised EOG signal) and of head position, and was differentiated (gaze velocity shown on the right). Eye and gaze signals were numerically filtered with a 30 Hz cut-off frequency. Note the clear difference in dynamics of gaze shifts between "target ipsi" and "head fixed" conditions.

Despite a VOR inhibition ranging from 15% to 70% (mean individual computed values) final gaze accuracy is not affected by head movement. This appears in Figure 3 where errors of gaze shifts are displayed in the three experimental conditions. A large variability of percentage error in both "head driven" conditions is observed, due to both intra- and inter-subject variabilities. However, the main result is the absence of significant differences between the three means. In particular, no trend in overshooting can be noticed in the "target ipsi" condition. As a result, the control of gaze accuracy seems to be quite efficiently achieved by a slight reduction of saccadic duration (see, for example Fig. 1). Thus, when head and eyes are both directed to the target, the same gaze shift amplitude is executed as when the head is fixed, although gaze velocity is faster in the first case.

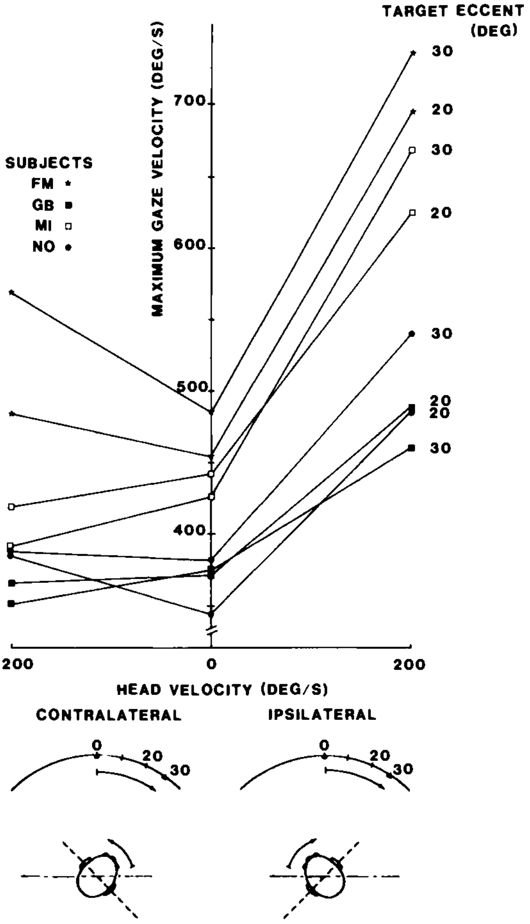

Figure 2

Maximum gaze velocity against head velocity. Averaged maximum gaze velocities are plotted for each experimental condition: "target contra" (-200), "head fixed" (0) and "target ipsi" (+200), and for each target step (20 deg and 30 deg) for the 4 subjects. In all cases, maximum gaze velocities are significantly greater in "target ipsi" condition than in "head fixed" condition ($p<0.01$); they are not significantly different between "target contra" and "head fixed" conditions (except for FM at 30 deg : $t_{14}=5.0$, $p<0.01$).

DISCUSSION

The global conclusion which can be drawn from this study is that the partial additivity hypothesis derived from cat's orienting behavior also applies to man when the head is passively rotated toward a visual stimulus. A similar conclusion was also reached in man in a study of whole body passive rotation (Jürgens et al. (1981b)) and by an observation in voluntary behavior of gaze orientation (Robinson and Zee (1981)). In order to insert our findings among today's concepts of gaze control, we present a very simplified functional block

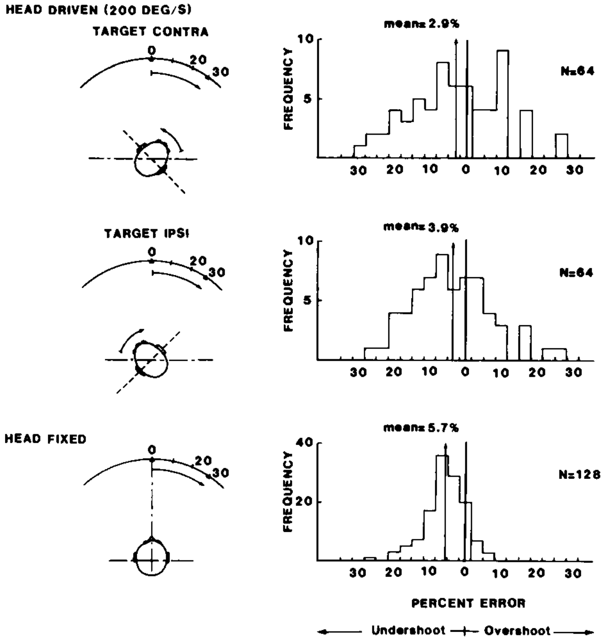

Figure 3
Accuracy of gaze shifts. The percent error (defined as (gaze shift - target step)/target step) is depicted for the three experimental conditions indicated on the left side. A rather large scatter appears in gaze accuracy in the two "head driven" conditions due to both intra- and inter-subject variabilities. No significant differences exist between the three means (heavy lines).

diagram (Fig. 4). This diagram is based on the concepts developped by Bizzi's group in the full additivity theory but shows two additionnal pathways (dashed-lines) to explain the present results. First, we shall consider the mechanisms suggested by the full additivity theory illustrated by the solid lines (so that $\hat{G}$ = Ec = estimate of eye position) and further assume that VOR gain K = 1. When a step of target position occurs, the peripheral target creates a retinal error (ε) which is sent to both saccadic and head motor systems. The output signals or neural commands (Ec and Hc) of the two systems reach the muscles nearly simultaneously (Warabi (1977) ; Biguer, Jeannerod and Prablanc (1982)).

When the head is free to move, the two commands lead to the classical eye-head orienting behavior : the global gaze shift is thought to be similar to saccadic eye movement alone with the head restrained, because a negative feedback loop through the vestibular system would provide a head position estimate $\hat{H}$ which would be fully subtracted (as K = 1) from the saccadic ocular command Ec. In addition, as the external visual feedback loop is opened during the saccade, a widespread hypothesis suggests that an internal feedback loop (the so-called "local feedback loop") providing an estimate of eye position (assume $\hat{G}$ = Ec) would control saccadic accuracy (Robinson (1975) ; Mays and Sparks (1980) ; Jürgens, Becker and Kornhuber (1981a)). Although we know that actual signals combine at the level of velocities before an integration phase, for the sake of clarity, we have instead represented position signals (Ec and $\hat{H}$). In addition, other mechanisms such as cervico-ocular reflex, optokinetic and pursuit systems, which to a lesser extent contribute to gaze stabilization during head movements, were voluntarily omitted.

The results of the present study suggest two additionnal functional pathways shown by the dashed-lines on Figure 4 :
a) a VOR gain inhibition ($K < 1$) during the saccade which could be controlled either directly or indirectly by the saccadic system;
b) a computation of an estimate of absolute gaze position ($\hat{G}$) by adding the head position signal ($\hat{H}$) derived from the vestibular system with the saccadic eye position command (Ec) or output signal of the saccadic system.

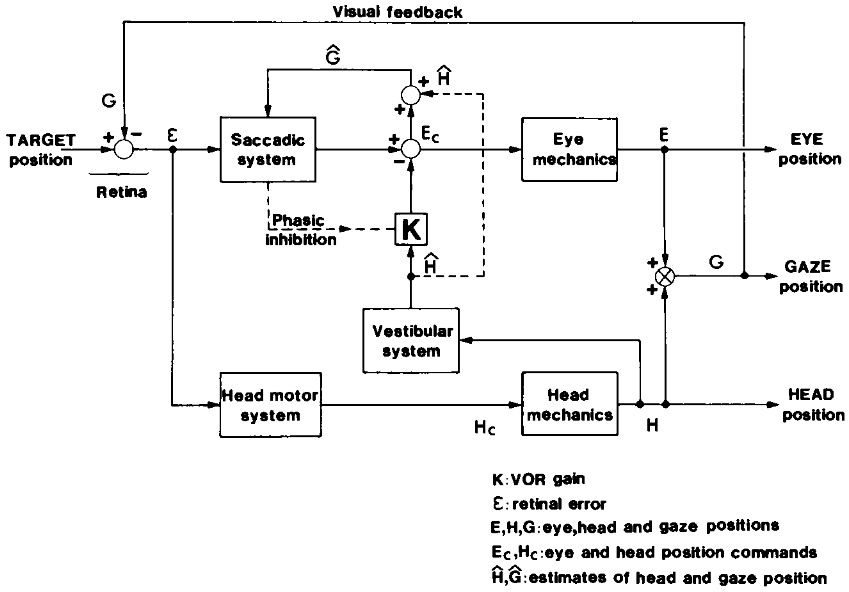

Figure 4
Simplified block diagram of partial additivity and gaze internal loop hypothesis. For the sake of clarity the boxes labelled "saccadic system" and "vestibular system" are supposed to contain their own neural integrator and thus to provide position output commands : Ec and $\hat{H}$ (see text). The diagram shows clearly the adding junction between saccadic ocular command (Ec) and head position estimated ($\hat{H}$) through the vestibular system assuming a unity VOR gain ($K = 1$) ; the solid lines representing the full additivity hypothesis. Two additionnal pathways (dashed-lines) are added to account for the present results. The first is an inhibition of VOR ($K < 1$) which is phasically triggered by the saccadic sytem and the second involves a computation of a gaze position estimate ($\hat{G}$) by adding actual head position ($\hat{H}$) of vestibular origin and saccadic command.

The first point is based on the observation of perfect stabilization of gaze in space achieved by a unity gain VOR before and after the saccade, despite a VOR inhibition during the saccade. This observation implies good timing between VOR inhibition and saccadic eye movement, and therefore indicates that VOR inhibition could be both triggered and stopped by the saccadic system. The second main point of the diagram is a hypothesis which would explain the accuracy of gaze shifts in the "head driven" condition. Let us consider the situation of a head movement in the same direction as the saccadic eye movement : if this latter was purely preprogrammed by the selection of the same duration of phasic activity as it is with head fixed, then the gaze would overshoot its goal when VOR inhibition is large. The same overshoot would occur if saccadic duration were controlled by the retinotopic local feedback loop. The absence of a trend in overshooting in the "target ipsi" condition supports neither hypothesis but rather suggests that the duration of saccadic activity must be determined by a continuous comparison between target position and actual gaze position. Thus a local feedback loop carrying gaze position estimate ($\hat{G}$), rather than eye position, would be more compatible with the data , as already suggested by some authors (Robinson and Zee (1981) ; Roucoux et al. (1980) ; Fuller et al. (1983)).

However, gaze landing points are much more scattered around target position in the "head driven" condition than in the "head fixed" condition, a result which could be accounted for by the passive rotation of the head. In natural conditions one can speculate whether a better coding of head position could be accomplished by using additional signals derived from the head rotation command (such as an efferent copy) not available in the present experiment. Further experiments in head free conditions are required to investigate this issue. Moreover, such studies of natural gaze orientation would probably give some indications as to the role (if any) of active head rotation on VOR inhibition during the saccade. As yet we have only some preliminary results supporting the hypothesis of VOR inhibition in agreement with Robinson and Zee's (1981) observations.

Additional observations can be made in the light of the present results. The main features of the diagram (dashed lines) are not purely theoretical: they have some electrophysiological correlates such as the vestibular pause neurons (Baker and Berthoz (1974) ; King, Lisberger and Fuchs (1976) ; Pola and Robinson (1978)) and the gaze burst cells described by Lestienne, Whittington and Bizzi (1981). Indeed, the first ones could represent a neural substrate of the variable gain VOR as they carry a vestibular signal which pauses during saccadic eye movements; the latter could drive the output of the summator between head and eye position ($\hat{H}$ and Ec) in the local feedback loop, as their firing rate is related to gaze position. Another indirect argument for a central computation of a gaze position signal comes from the recent observation of cat tectal neurons firing in relation to the error between gaze and target positions (Munoz and Guitton (1985)).

Although our data and the above electrophysiological findings are in agreement with the partial additivity hypothesis, one can speculate about other possible mechanisms. Among them, a non-specific hyperactivation of the saccadic system due to vestibular stimulation could have raised the saccadic gaze velocity. If this explanation alone was true, i.e. without VOR inhibition, a similar increased saccadic gaze velocity should have been observed in both head driven conditions ("target ispi" or "target contra"), compared to head fixed condition. The absence of systematic difference between "target contra" and "head fixed" is sufficient to rule out this hypothesis as an exclusive one. Alternatively a combined VOR inhibition and saccadic hyperactivation as suggested by Jürgens et al (1981b) could well account for our data. Indeed these two effects could add (increasing gaze velocity) when eye saccade and head go in the same direction and could cancel each other when eye saccade and head go in opposite directions. A last possibility is the absence of saccadic hyperactivation and a unilateral VOR inhibition, which would account for the unexpected asymmetric change in gaze velocity under ipsilateral or contralateral head motion.

In conclusion, though it is not possible to make a clear cut between the two last hypotheses, a partial inhibition of the VOR has been shown to occur during passive head movement. In addition the accuracy of saccadic gaze shifts is indirect but strong support for a local feedback loop allowing an on-line computation of gaze position.

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EYE MOVEMENTS: From Physiology to Cognition
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FIXATION SUPPRESSION OF THE VESTIBULAR OCULAR REFLEX AND HEAD MOVEMENT CORRELATED EEG POTENTIALS

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Fast voluntary horizontal head movements were recorded in 30 healthy volunteers while they were viewing a head fixed targed in darkness. Selective averaging of the fastest movements revealed a biphasic cortical potential. Median latency of its onset was 123.5 msec, of its first peak 189 msec, of the second peak 373 msec, with amplitudes ranging around 5.7 myV. Similar recordings in patients with uni- or bilateral vestibular nerve lesions demonstrated that strong stimulation of joint vestibular and somatosensory (neck afferent) input facilitated characteristically related EEG activity.

INTRODUCTION

Vestibularly induced cortical potentials in humans have been described by various authors using galvanic (Molinari and Mingrino (1974)), postrotatory (Spiegel, Szekely and Moffet (1968)) or perrotatory (Bumm, Johannsen, Spreng and Wiegand (1970), Greiner, Collard, Conraux, Picart and Rohmer (1967), Theissing (1970)) stimulation including passive accelerations comparing vestibular and optokinetic stimulation. These studies in humans have been corroborated by animal studies that evaluated the integration of somatosensory and vestibular afferent input on different levels of the central nervous system (CNS) as well as the location of the primary vestibular field in different species using electrical stimulation. Most studies were directed toward identifying pure vestibular responses: either early responses elicited through electrical stimulation of the nerve using surface electrodes. Widely differing results in humans have been reported - with conclusive evidence showing the primary vestibular area to be located in various animals in area 2v and 3a (Kornhuber and Dafonseca (1964), Schwarz and Frederickson (1971), Oedquist, Larsby and Frederickson (1975), Elidan, Sohmer and Nizan (1982)) with latencies around 5-6 msec. Gruesser, Pause and Schreiter (1982) reported neuronal responses to natural vestibular stimulation in the parieto-insular cortex of alert Java monkeys, but did not mention latencies.

"Vestibular" responses in humans of later ocurrence showed much more variability (80-500 msec) due to the different modes of stimulation.

Only Salamy, Potvin, Jones and Landreth (1975) tried to link subjective and objective results with respect to sensation of movement. Since methods of pure vestibular stimulation were applicable only in animals or lacked a reasonably high reproducibility, until now testing of cortical "vestibular" responses has not been used either clinically or in comparison to psychophysically oriented studies.

Another difficulty of studies in humans has been the especially high vestibular-somatosensory spread within the CNS (Frederickson, Kornhuber and Schwarz (1975), Buettner and Buettner (1978), Deecke, Schwarz and Frederickson (1973)). It has been known for a long time that vestibular stimulation may be followed by disinhibition of epileptogenic foci or increased responses to other sensory inputs with a concurrent change of electroencephalographic (EEG) activity (Molnar (1959)). There is ample evidence suggesting that vestibularly evoked cortical activity in areas other than 2v

(Kornhuber and Da Fonseca (1964)) and 3a (Oedquist, Larsby and Frederickson (1975)) is mediated via long polysynaptic pathways, including the arousal system of the brainstem reticular formation and medial thalamus (Frederickson, Kornhuber and Schwarz (1975), Liedgren, Milne, Rubin, Schwarz and Tomlinson (1976)). Supposedly this kind of reflex activity occurs together with orienting responses. Vestibular stimuli cause more arousal reactions than other sensory stimuli, except for pain. They tend to produce non-specific responses in almost all cortical areas (Kornhuber and Da Fonseca (1964)).

The aim of this study was to show that a cortical potential can be obtained using a strong natural vestibular stimulus that is also linked to related input from neck afferents. Furthermore, it should eventually reveal the possibility of distinguishing the effect of vestibular from the joint proprioceptive input by comparing results in healthy subjects to patients with uni- or bilateral vestibular loss.

METHODS

NORMAL SUBJECTS. 30 healthy volunteers (age 20 to 30) took part in this study, most of whom participated two to four times on different days. Subjects sat in a comfortable chair in total darkness and quiet. They were asked to perform fast, horizontal active head movements (n = 400) within an angular amplitude of ±20 deg and a pause of 1 to 3 seconds between these movements while they were viewing a head-fixed small red target from a distance of 30 cm. Maximum angular horizontal accelerations ranged in this way around 8500 deg/sqsec.

PATIENTS. In an attempt to disinguish vestibular and non-vestibular influences on the EEG occurring synchronously with head movements, we checked ten patients with vestibular disturbances (age 23 to 54, six female, four male). Four of them had had univestibular loss for 3 to 10 years after vestibular neurectomy. Six of them had lifelong auditory and vestbular loss because of congenital malfunction of the inner ear.

EEG RECORDINGS were done using platinum needle electrodes that were attached to the head with collodium. Cable artifacts were minimized using preamplifiers and impedance adaptors firmly linked to the head. Electrodes were set according to the 10-20 system, with bimastoidal common reference (Cb1 and Cb2). Electro-oculographic (AC EOG) recordings had a time constant of 1 sec. Head acceleration was measured with a high precision angular accelerometer (Schaevitz, no. A S13C-1500) firmly mounted onto a light-weight adjustable circular head frame, tightly linked to the subject's head. For each movement direction the fastest 50 to 100 single trials were selected after visual inspection, using maximum steepness of initial acceleration as the selecting criterion. After his pre-editing procedure averaging was done using 2/3 of maximum positive acceleration as trigger point.

CONTROL STUDIES. In order to evaluate the possible number of pure reafferent potentials in our experimental condition WITHOUT any head movement, we did additional experimental trials using reciprocally executed flexion-extension movements of the wrists and rotation of the trunk with head fixed (Fig. 1). When considering only the fastest movements - as we did with the head movements - only very small late reafferent potentials showed up. Eye movement artifacts from presaccadic activity, lambda waves, or EOG potentials were avoided or minimized by the experimental procedure. Additionally, rejection of persisting eye movment artifacts was done using an earlier described analog device (Girton and Kamiya (1973)).

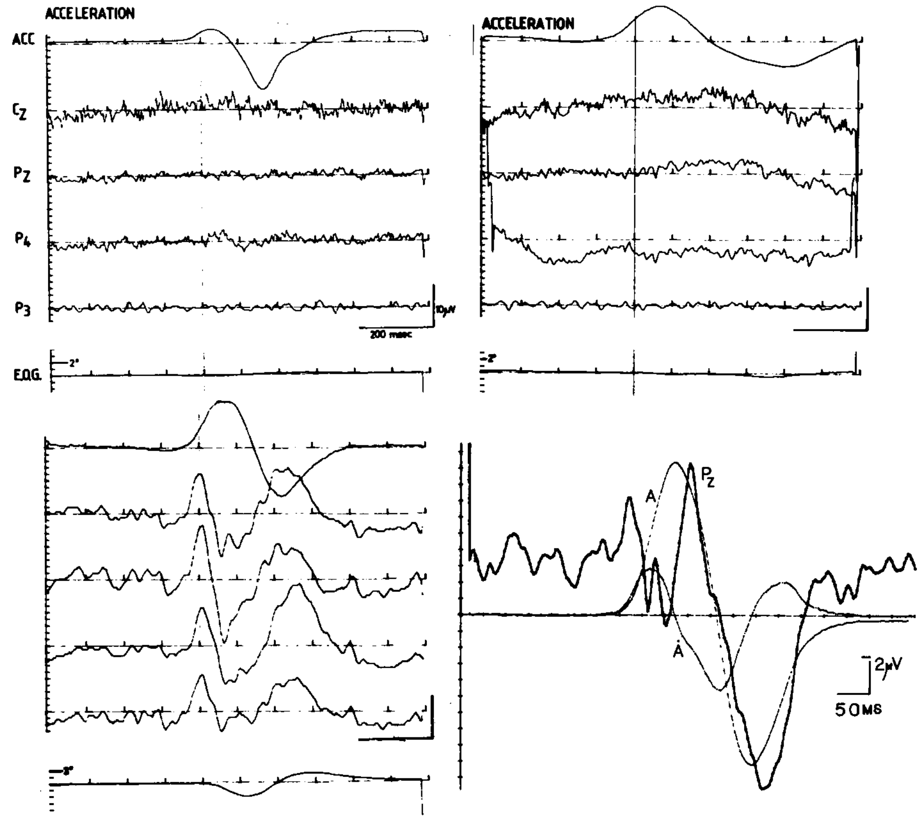

Figure 1 Figure 2

Comparison of average recordings of fast wrist rotations (upper left, 9500 deg/sqec), trunk rotations with fixed head (upper right, 2600 deg/sqsec) and (lower left, 9750 deg/sqsec) head rotations (same subject, n=75). On lower right unipolar EEG (Pz/Cbl-2), acceleration (A) and acceleration's derivative (A dot) of another subject (n=60) are displayed. Note the first, smaller negative peak (85 msec), coinciding with A dot maximum, the shorter latencies of the following deflections (N 172 msec; P 340 msec), and the greater steepness of EEG deflections with increasing briskness of averaged movements (A_{max} lower: 9800 deg(sqsec, upper left: 9200 deg(sqsec, upper right: 8330 deg(sqsec).

RESULTS

LATENCIES, VARIABILITY. Averaging of pre-edited records of similarly fast head rotations (n=100 to each side) demonstrated a characteristic biphasic potential (Fig. 3). Latencies measured from onset of acceleration to the first -negative- peak (t2) ranged between 154.5 and of 5.7 microvolt. Unipolar recordings were preferred for measurement of latencies, since polar recordings could obscure latencies and patterns of potentials by phase shifts. The second -positive- peak showed some greater variability (t3; 280 to 418 msec) with a median of 373 msec and an average amplitude of 5.8 microvolt.

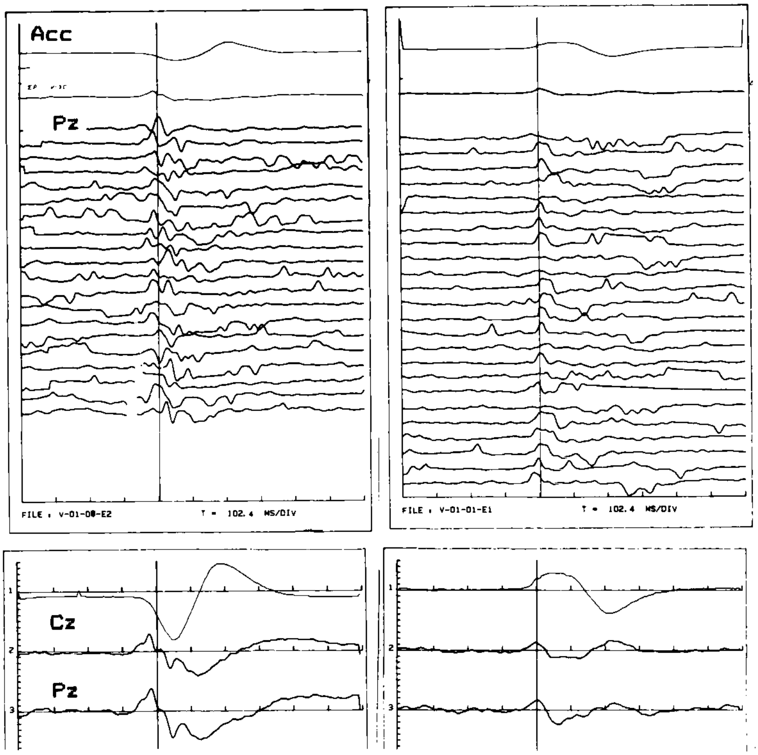

Figure 3

Increase of averaged (lower, n=50) EEG responses with increase of acceleration of head movements. Single responses (upper) demonstrate the positive relation of EEG with acceleration (left: 9400 deg/sqsec; right: 3200 deg/sqsec)

An averaged recording (n=60) from another subject (Fig. 2; Pz/Cbl, 2) demonstrated a very fast and symmetrical acceleration trace (A) as well as of its derivative (Adot = "jerk"). The respective values for t2 and t3 were 172 msec and 340 msec. In addition, this example showed an early negativity of 85 msec latency with respect to acceleration onset, which was seen only with faster movements. A positive correlation between clearly defined jerk (Acc. derivative) peaks and this early negativity was noted.

ACCELERATION DIFFERENCES, SIDE ASYMMETRIES. Differences with respect to the direction of rotation could be seen but did not appear to be significant. However, clear differences according to movement dynamics were found: e.g. (Fig. 3) the rightward movement that lasted longer, had a lower maximum acceleration and lower rise of initial acceleration than the leftward movement. Respective EEG recordings demonstrated a flatter and later response for the slower movements. Comparison of small and large head movement amplitudes with quite different accelerations indeed demonstrated a larger response and more pronounced side asymmetries, because of the main sequence relationship (Zangemeister, Jones and Stark (1981)) for very fast movements. As the time to build up large accelerations during a large movement was significantly longer than for smaller movements, related averaged EEG responses appeared to occur later. Comparison of the sum of single responses of slow and fast head movements within the same experimental set showed a similar effect (Fig. 3).

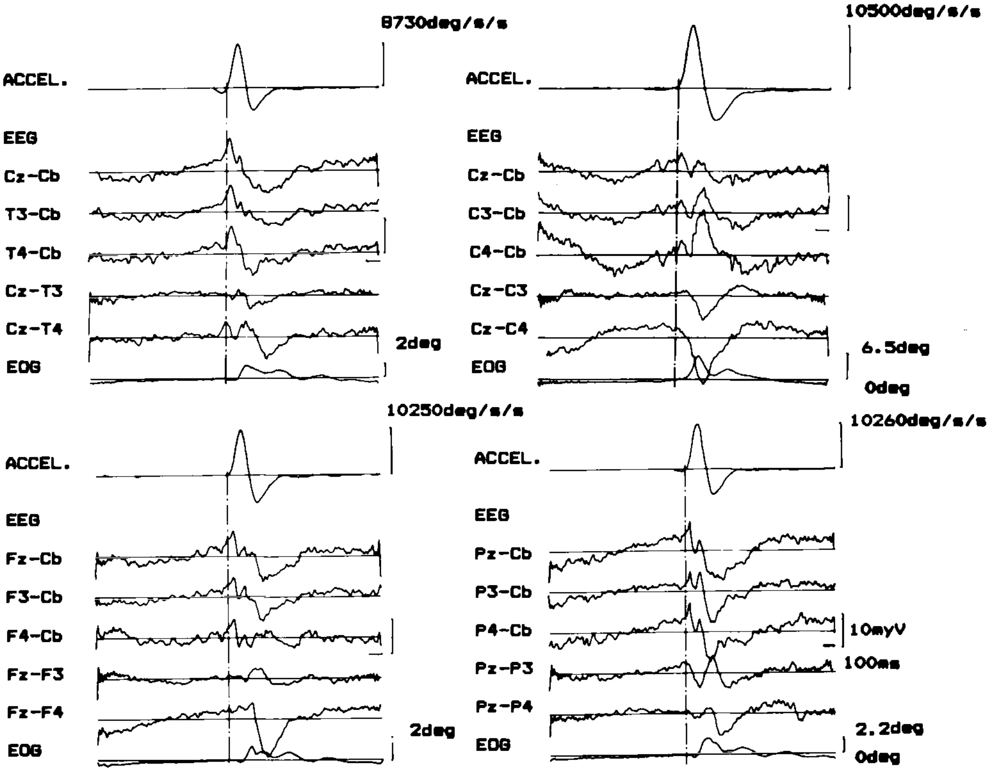

Figure 4

Reproducibility and differences with respect to different recording locations: fronto-precentral (upper left), temporocentral (lower left), central (upper right), parietal (lower right). Same display made as before, n=75. Note larger EOG deflection with higher acceleration (upper right).

DIFFERENT RECORDING LOCATIONS. When several different electrode locations were compared (e.g. frontal, central, parietal, temporal), characteristic differences of the averaged EEG responses were observed (Fig. 4). Fronto-precentral recordings displayed a consistent early first peak of 85 msec latency that was also seen in the parietal leads. With temporal and central recordings, this peak hardly showed up. As far as side asymmetries were concerned, frontal and central bipolar recordings showed the largest differences contralateral to the direction of rotation. The characterisitc change of polarity of the evoked potential could be demonstrated by comparison of precentral with postcentral recordings (Fig. 4). As expected from earlier results, the centroparietal recordings appeared to reveal the highest information content.

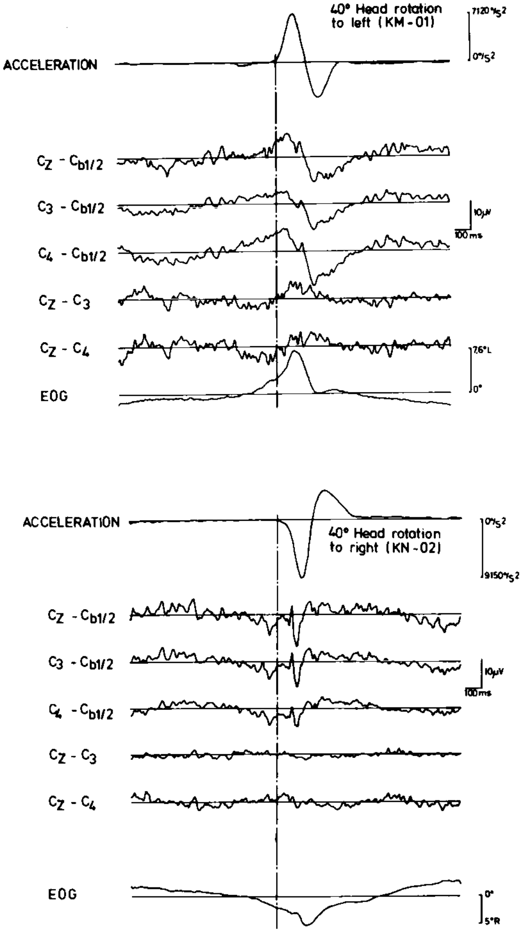

Figure 5

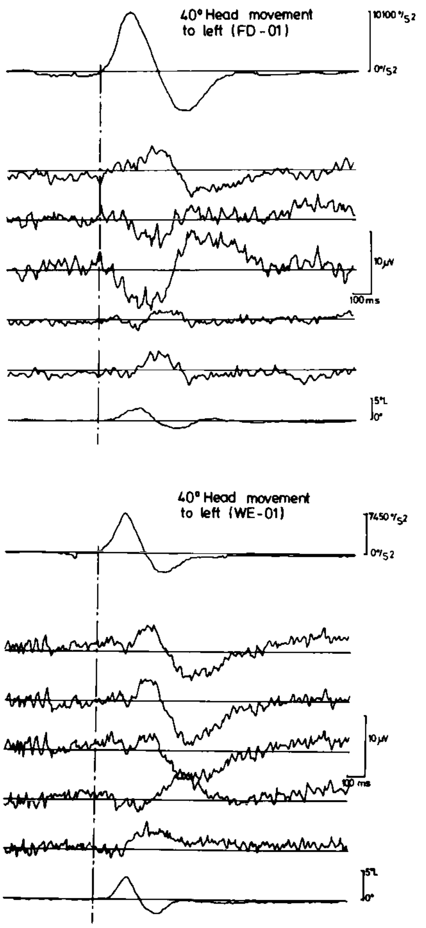

Figure 6

Recordings of a patient with unilateral vestibular neurectomy (M. Meniere) on the left side. Movements contralateral to operated side (n = 70, lower) give no typical EEG response except for an early negative-positive peak around 90 msec, that was not seen in almost "normal" EEG pattern. Fig. 6: Recordings of two patients with congenital vestibular loss. Note the similar pattern but comparatively low amplitude with respect to recordings in healthy subjects (upper n = 55, lower n = 60; EEG polarity reversed).

UNILATERAL VESTIBULAR LOSS. Patients (n = 4) with unilateral vestibular neurectomy many years before time of testing, demonstrated a clear side asymmetry. Movements contralateral to the lesion generated no comparable response as in normal healthy subjects. Ipsilaterally directed head rotations however, were followed by a quite "normal" averaged EEG potential (cf. Fig. 4b). Interestingly, fixation suppression of eye movements was less accurate in these patients, demonstrated by early smooth beginning of the EOG trace, starting shortly before acceleration onset (Fig. 5). The early fast EEG components similar to those that were best seen in the precentral recordings (Fig. 4a), were not consistently recorded with movements contralateral to the lesion.

BILATERAL VESTIBULAR LOSS. Patients (n = 6) with a lifelong (congenital) bivestibular loss generally showed particularly low response amplitudes (Fig. 6, note calibration). Using high amplification a similarly formed potential of respective latencies as in our normal subjects was observed. Characteristically, the concurrent eye movements of these patients lacked any compensatory aspect, but rotated almost synchronously with the head acceleration into the same direction (anticompensatory, Fuller 1980).

DISCUSSION

The main finding of this study was that there is a characteristic potential occurring with fast self-paced head movements while viewing a head fixed target in darkness. It was most regularly seen over centro-parietal regions. It showed a comparable and reproducible pattern, latency and amplitude in 30 healthy subjects. Average latencies amounted to 190 msec (N190) and 370 msec (P370), with an earlier negative peak (N85), which was seen only with very brisk, fast movements. Acceleration magnitude appeared to have a positive effect on amplitude and latency of this potential; but this finding needs a more detailed study, before further conclusions can be drawn.

Artifacts of physiological and non-physiological origin have been considered very carefully. For additional discussion of these and of earlier results relating EEG and vestibular stimulation see Zangemeister, Phlebs, Huefner and Kunze (1986) and also the final part of the method section.

PREVIOUS STUDIES. The lack of agreement among previous investigators attempting to obtain rotatory evoked responses can be attributed to differences in the methods used. Differences in subject testing position (seated, semisupine, supine), differences in recording sites (temporo-occipital, temporo-vertex, vertex-mastoid), and in stimulus amplitude may explain the differences between former studies. The main difference between our study and related studies was a definite peak of a maximal angular acceleration, an almost total exclusion of eye movements, the selective averaging, and the inclusion of proprioceptive influences from neck movement. We believe that these differences provide clear advantages with respect to previous studies in terms of reproducibility of a well defined stimulus and improved signal analysis.

VESTIBULO-SOMATOSENSORY CONVERGENCE. According to Frederickson, Kornhuber and Schwarz (1974), as well as many other researchers already mentioned, two systematically different neocortical fields which meet the criteria for a primary vestibular projection have been identified in different mammalian species: area 3a in the squirrel monkey, which is located between sensory and motor cortex and is believed to participate in motor function. Area 2v, the second vestibular field, is located posterior to the first somatosensory field (parietal lobe in the rhesus monkey). Its presumed function is conscious integrated perception of body position and movements. The common denominator of both areas is the convergence of vestibular and deep somatic afferents, in 2v predominantly from the joints, in 3a from muscle spindles. A similar convergence is well established in the motor cortex, in the vestibular nuclei, and in the thalamic nucleus (Kornhuber and Da Fonseca (1964), Frederickson, Kornhuber and Schwarz (1974), Deecke, Schwarz and Frederickson (1973), Liedgren, Milne, Rubin, Schwarz and Tomlinson (1976)). Thus information from the peripheral vestibular organ is not transferred separately to the cortex, but together with other sensory modalities, all of which can be used for control and perception of posture and movement. The signal in the vestibular nucleus, which is already a composite signal from different sensory systems, appears to undergo some further information processing at the thalamic and cortical level.

About 50% of vestibular nuclei neurones showed an additional eye movement related modulation, which was not found at the thalamic and cortical level (Buettner and

Buettner (1978)). This indicates that the ascending vestibulocortical pathway does not participate in the VOR.

NECK PROPRIOCEPTION and ACTIVE HEAD MOVEMENTS. In view of the findings referred to, it becomes evident that a "specific" monomodal vestibular evoked potential cannot be obtained. What could be obtained however, is the relative proponderance of one modality that might occur with a specific stimulus. Concerning the sensation of angular acceleration, this has been described by Zangemeister, Stark, Meienberg and Waite (1982) and Salamy, Potvin, Jones and Landreth (1975). With increasing velocity of active movements, the threshold of movement sensation is elevated and the amplitude of the SEP or SSEP is decreased (Angel (1982), Papakostopoulos (1975)).

Stimulation of cervical proprioceptors by torsion of the neck results in movement of the eyes. The pathways of this neck-eye reflex have been identified electrophysiologically. In individuals with VOR deficits the reflex is often seen to contribute to retinal image stability during head movements. In normal individuals, however, its role in ocular compensation is questionable (Fuller (1980)). In four species of mammals (rat, rabbit, cat monkey), the reflex was most consistently elicited with an anticompensatory phase, and it appeared to be absent when the animal ACTIVELY moved its head (Gresty (1976), Fuller (1980)). In HEALTHY humans, the neck-eye reflex does not appear to have a significant role. It becomes, however, functionally important with vestibular deficits as reported by Kasai and Zee (1978), Zangemeister and Stark (1983), and for monkeys by Dichgans, Bizzi, MOrasso and Tagliasco (1974).

Studies comparing passive and active limb movements have demonstrated that the well known (Kornhuber and Deecke (1965)) reafferent potential shifts in conjunction with passive movements can not be obtained any more during very fast active movements (Papakostopoulos, Cooper and Crow (1975)). A comparatively low amplitude negativity (N160) and a late positive deflection (P300) were found (Shibasaki, Barret, Halliday and Halliday (1980)). Similar evidence comes from our trials with normal sujects reciprocally flexing and extending their wrists. These results confirmed the mentioned results by others, indicating that with very fast active movements reafferent EEG potentials tend to be diminished. In particular. Papakostopoulos, Cooper and Crow (1975), reporting from chronically implanted electrodes in six subjects noted that in all subjects tested with fast selfpaced finger displacements no response could be registered from the prefrontal areas, only a broad positivity developed in the postcentral areas, and in the precentral areas a diminished amplitude response could be seen in the form of a negative peak. We infer from this evidence that with the very fast active head movements used in our study, the influence of reafferent EEG potentials is low. The reported potential shifts appear therefore related to other sensory influences, i.e. the strong vestibular stimulus. On the other hand, the Bereitschaftspotential (BP) and premotor potential (PMP) (Kornhuber and Deecke (1975)) related to well controlled active movements could be demonstrated in our recordings, as can be seen in Figure 4.

CLINICAL EVIDENCE. Given this evidence, the experimental maneuver used in our study provided a clearly defined condition of a particularly high threshold for proprioceptive input from the neck. At the same time, it provided a sufficient suppression of eye movements during vestibular stimulation by fixation suppression of the VOR. So it appears reasonable to relate the demonstrated shifts of head acceleration correlated cerebral potentials mainly to vestibular influences rather than to other ones. Direct evidence for this comes from experiments reported by Boehmer, Henn and Lehmann (1983). They found after brisk passive accelerations of 2000 deg/sqsec in rhesus monkeys an early positive peak around 45 msec, and a later occurring negative peak around 90 msec when using head rotation alone or body plus head rotation. When using isolated body rotation with head fixed, however, these peaks were abolished. Further evidence comes from our recordings in 10 patients with uni- or bivestibular loss.

We conclude that cortical responses to brisk active head rotations are comparable to those of other sensory modalities. Generally, vestibular tests study only vestibulo-spinal or vestibulo-ocular reflexes, or subjective sensations. The present report suggests a method whereby vestibulocortical responses may also be studied. Since the evoked potential method is fast and non-invasive, it may be well suited for clinical use.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

TARGET POSITION: A STIMULUS FOR SMOOTH PURSUIT EYE MOVEMENTS IN THE MONKEY

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We have examined the role of target position (offset from the fovea) in the control of monkey smooth pursuit eye movements. Monkeys tracked open-loop square-wave target motion. (The square-wave was stabilized at the fovea so the target jumped from one side of the fovea to the other, regardless of gaze direction). The square-wave stimuli produced slow sinusoid-like eye movements interspersed with saccades. Response velocity increased with target offset from the fovea up to 2 deg. A notable finding was that the response to each offset was highly variable. This variability may be related to the monkey's level of attention.

INTRODUCTION

Target motion is generally required to make a smooth pursuit eye movement and this has led to the traditional view that it is the velocity of the moving object relative to the retina (retinal slip velocity) which is the stimulus for pursuit (Young and Stark, 1963; Robinson, 1971, 1976; Zee, Friendlich and Robinson, 1974). The main support for retinal slip velocity as the stimulus for pursuit eye movements comes from an experiment by Rashbass (1961). He asked subjects to visually follow a small target that made a step-ramp motion; the target jumped abruptly (the step) away from the fovea in one direction and then immediately returned at a constant velocity (the ramp) back towards the starting position. Typically, subjects made smooth pursuit eye movements in the direction of the ramp motion before the target crossed its original starting position. In other words, the smooth eye movements were in the direction of target velocity, not target position.

However, a number of observations cannot easily be explained if retinal slip velocity is the only stimulus for pursuit (e.g., smooth tracking of after-images), and recent studies indicate that target position (offset) relative to the fovea can also drive the pursuit system (Pola and Wyatt, 1980; Wyatt and Pola, 1981). While the idea of target position as a stimulus for pursuit has gained support (Becker, 1981; Eckmiller, 1981; Miles, 1982), the evidence for this has come essentially from human experiments, except for a preliminary study using monkeys (Morris and Lisberger, 1983).

The aim of this study was to examine the role of target position in the control of monkey smooth pursuit eye movements. This was assessed by examining tracking responses to open-loop square-wave target motion. (The center of the square-wave was stabilized at the fovea so the target jumped from one side of the fovea to the other, regardless of the monkey's direction of gaze.) As target velocity on the retina was zero except for brief jumps, the square-wave target motion is considered to be a pure position stimulus.

METHODS

Monkeys were trained using operant conditioning procedures to look at a small (1/8 deg) target and to visually track the movement of the target. (Detection of a brief dimming of the target was rewarded.) The monkey was seated at the center of a large semi-circular screen at a viewing distance of 165 cm. The target was projected onto the screen and could be moved horizontally by a servo-motor controlled mirror (General Scanning). This system has a bandwidth of 0-115 Hz. Horizontal and vertical eye position were monitored by the search-coil technique (Fuchs and Robinson, 1966; Judge, Richmond and Chu, 1980). Head position was fixed by way of a metal crown permanently attached to the animal's skull (Friendlich, 1973). Target position, eye position and eye velocity were recorded using a magnetic tape recorder (Vetter) and a polygraph (Beckman). To obtain open-loop stimulation (target motion stabilized on retina), a signal of horizontal eye position was added to the signal creating square-wave target motion and this sum drove the servo-motor. To calibrate the system, the monkey visually fixated in turn three stationary targets located straight ahead and at 20 deg to right and left of center. During calibration, the open-loop pursuit target was turned on and stabilization checked: the criterion for good stabilization was that the square-wave target jump symmetrically about each fixation light. Stabilization was checked before and after each trial.

During an experimental trial, the monkey's task was to track the horizontal motion of the target at one square-wave frequency and amplitude. Each trial began with closed-loop square-wave target motion. After a number of cycles, the square-wave target motion became open-loop (square-wave motion stabilized about the fovea) and tracking continued for 20 seconds. Peak-to-peak square-wave amplitude was varied from 0.5 to 6 deg (and thus target offset to each side of the fovea was 0.25 to 3 deg). Several frequencies (0.5, 0.75, 1.0, 1.5 Hz) of square-wave target motion were used. The sequence of target offset and frequency was randomized, and a number of trials were performed in each condition. Peak smooth eye velocity was measured by hand from the eye velocity record.

RESULTS and CONCLUSIONS

Figure 1 shows typical slow eye movement responses, from one monkey, to square-wave target motion stabilized on the retina at three offsets and at two frequencies. Records are of original data and show both eye position (E) and target position (T). The records show that the monkey in attempting to look at (track) the target made smooth sinusoid-like eye movements interspersed with saccades, towards the target position. The records also show that as the size of the offset (square-wave) increased, faster slow eye movements occurred. In Figure 2, the mean value of the peak smooth eye movement velocity (for the same monkey) is plotted as a function of target offset from the fovea at the four square-wave frequencies used. Peak smooth eye velocity increased with target offset up to offsets of about 1.5 to 2 deg. For these larger offsets, smooth peak eye movement velocities in excess of 40 deg/sec often occurred. At offsets greater than 1.5 to 2 deg the response saturated and fell off. This was seen at all frequencies, suggesting that target position as a stimulus for pursuit is most powerful within 1.5 to 2 deg of the fovea. Essentially the same type of results were obtained from a second monkey used in these experiments (although a modified training procedure was used for this monkey - see below).

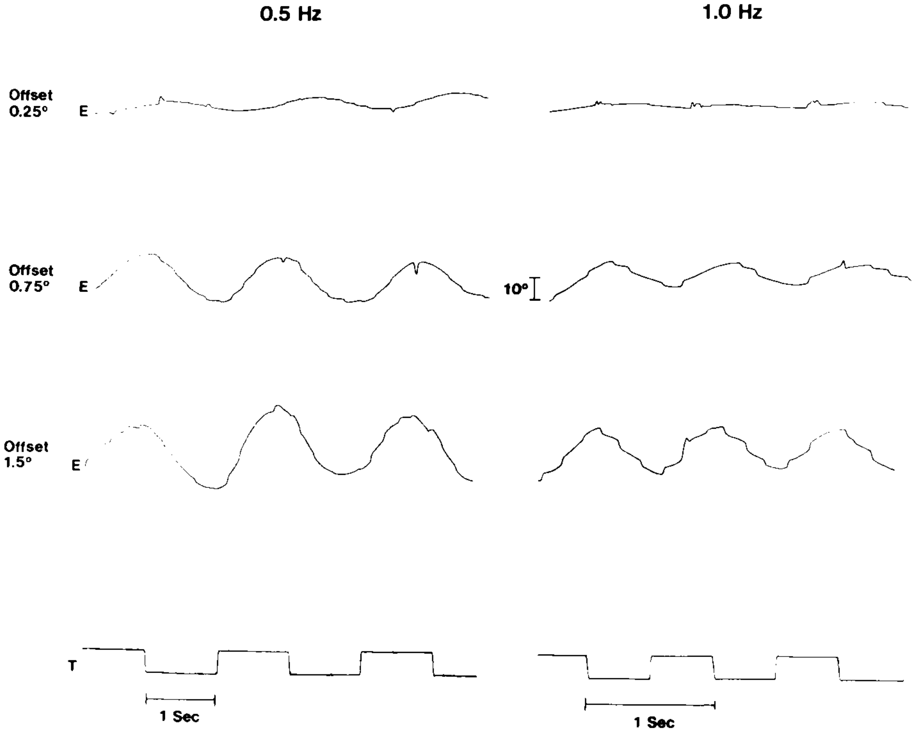

Figure 1. Eye movement responses to square-wave target motion stabilized on the retina at three offsets (0.25, 0.75, 1.5 deg) and at two frequencies (0.5, 1.0 Hz). Records are of original data and show both eye position (E) and target position (T).

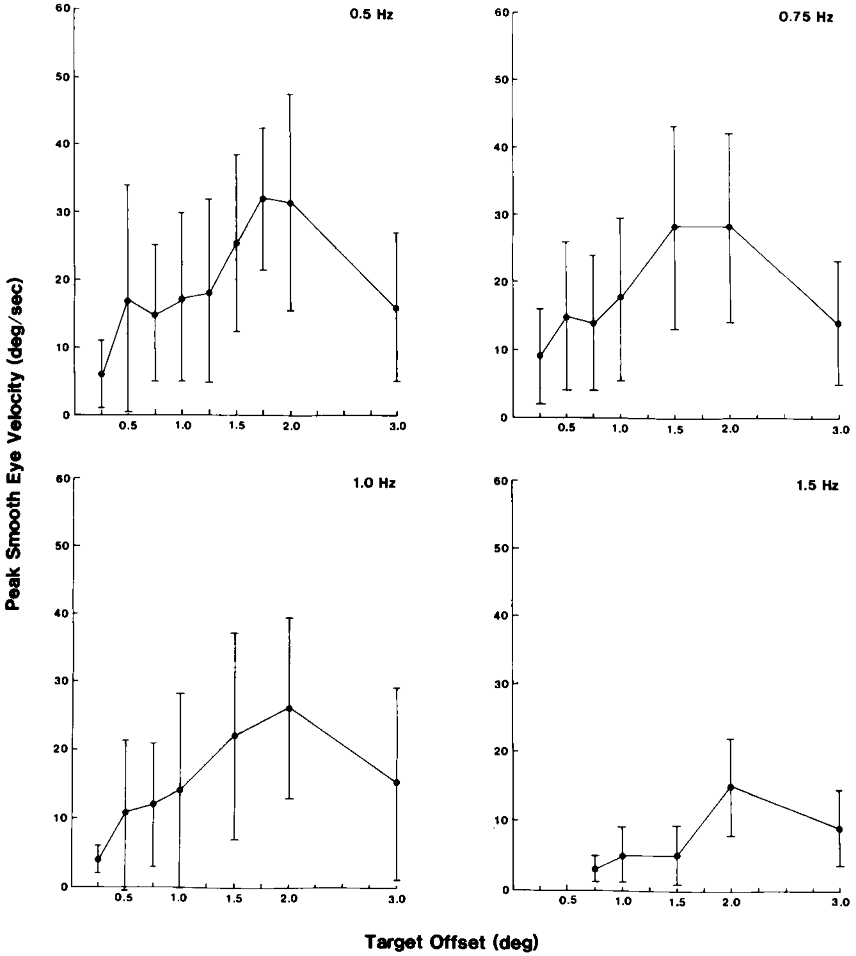

Figure 2. Overall mean value of peak smooth eye movement velocity versus target offset from the fovea at the four frequencies (0.5, 0.75, 1.0, 1.5, Hz). Error bars represent ±1 SD.

The data show considerable variability in the level of the smooth pursuit response to target offset both within and between trials (note large standard deviations in Figure 2). To account for this, one possibility is that the monkey's smooth pursuit response is related to the monkey's level of attention, so that smooth pursuit increases as closer attention is paid to target offset from the fovea. Thus, the pursuit response would be quite variable if the monkey's effort in trying to look at the target varied considerably within an experimental session and also from one session to another. Some support for this account comes from the observation that more tasty rewards (apple juice as opposed to water) tend to elicit more vigorous responses. In addition, we found that the second monkey used in these experiments (whose data is not shown here), when trained in the manner described in the methods, made mostly saccadic eye movements to the square-wave target motion and only occasional smooth pursuit. However, after we employed a modified training procedure which required the monkey to accurately track a moving target and thus presumably pay close attention to its motion (the monkey had to keep its eye within an "electronic window" which moved along with the target, to obtain her reward), the monkey began to show vigorous smooth pursuit movements to the square-wave target motion. Furthermore, the standard deviations for this pursuit were notably smaller than those shown in Figure 2.

These results show that target position can serve as a potent stimulus for monkey smooth pursuit. Furthermore, the smooth pursuit response to target position does not appear to be purely stimulus-bound; it may be that the response levels can be modulated by internal states.

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EFFECT OF VISUAL INPUT IN MOTOR PROGRAM OF SACCADES.

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Many reports suggest that vigilance level modifies spatial and temporal characteristics of saccades (Fuchs and Ron 1968; Crommelink and Roucoux 1976; Bon, Corazza and Inchingolo 1980). The aim of this research is to verify whether motor programs of eye movements are modified by visual input. The experiments were carried out on one monkey (Macaca nemestrina) trained to track targets. Horizontal and vertical components of eye movements were derived using search coil and the magnetic field technique. The analysis of eye movements was done off-line by a PDP 11/23 and by a graphic unit. Analogue signals were converted into digital signals using a sample frequency of 200 Hz and subsequently filtered to 50 Hz by a low pass filter. The digital filter of non-recursive FIR type did not introduce any phase distortion. The eye movements were recorded in darkness, under laboratory lighting and between targets. Three types of velocity pattern were identified : symmetrical(1)---asymmetrical(2) ---irregular(3). The first is when the time spent to reach the peak velocity and to come back zero velocity are equal (Fig.1). The second is when the time spent is different in the two phases (Fig.2). The third is when the peak velocity reached a plateau or when the pattern shows many variations of velocity (Fig.3).

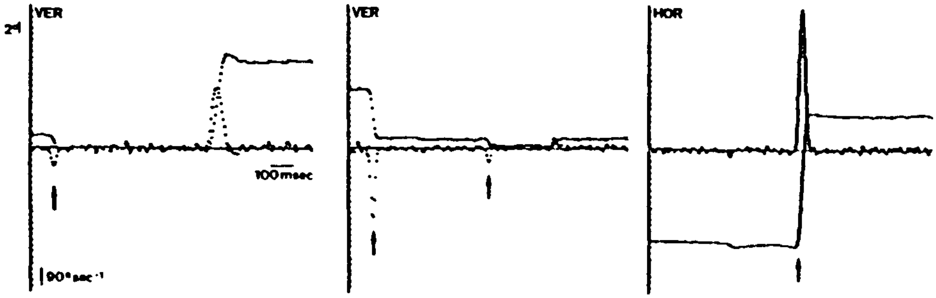

FIG 1-Horizontal (HOR) and vertical (VER) eye movements, with symmetrical pattern of velocity (↑).

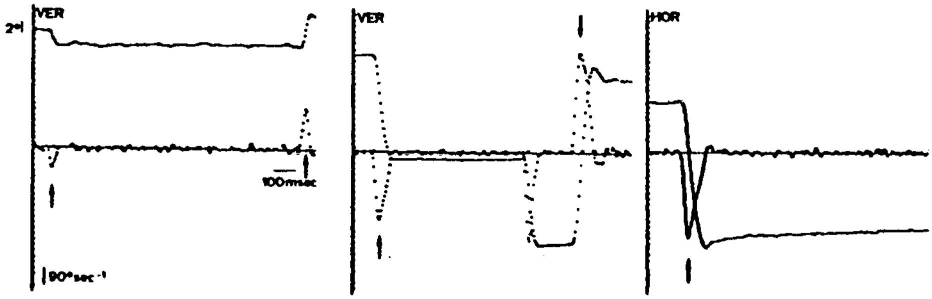

FIG 2-Horizontal (HOR) and vertical (VER) eye movements, with asymmetrical pattern of velocity (↑). ,

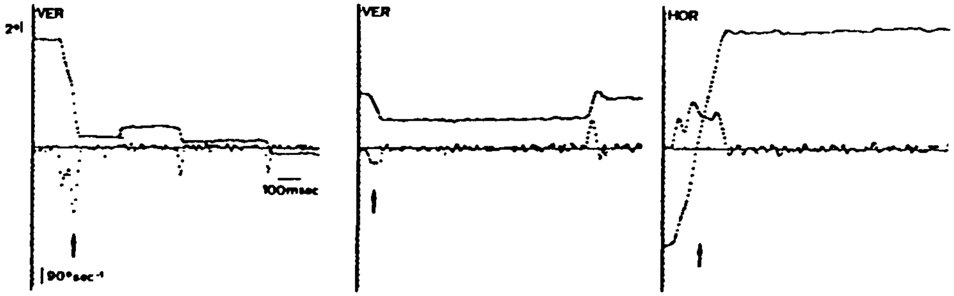

FIG 3-Horizontal (HOR) and vertical (VER) eye movements, with irregular pattern of velocity (↑).

From the statistical analysis of three hundred eye movements for each condition, we found that the per cent distribution of velocity patterns was different in dark, laboratory light and with target (table):

	DARK			LAB. LIGHT			TARGET		
	1	2	3	1	2	3	1	2	3
HOR	3.5	29.5	67.0	4.5	42.5	53.0	64.5	35.5	0.0
VER	9.0	57.0	34.0	10.5	56.0	33.5	58.5	41.5	0.0

These results show no substantial difference in distribution between DARK (no visual stimuli) and LAB. LIGHT (visual stimuli). However, in the TARGET situation (the animal made saccades between visual stimuli with an attentional meaning) the irregular pattern is not present. This suggests that visual input modifies motor programs, but,according to Dichgans,Nauck and Wolpert(1973),it is likely that attentional meaning is necessary to modify saccadic motor programs.

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PARIETAL CORTEX AND

S. FAUGIER-GRIMAUD and J. VENTRE

INTRODUCTION

Posterior parietal cortex in primates and especially area 7 is usually considered as an associative zone dealing with orientation in space, a procedure which requires continuous readjustments relying on input signals from different sensory modalities.

Electrophysiological data have pointed out that some of the polymodal neurons of this posterior parietal cortex respond to vestibular stimulation (Kawano et al 1980, 1984; Grusser et al 1982). The present work reports on the possible role played by this area in controlling vestibulo-ocular output and the possible routes for vestibular afferences.

METHODS

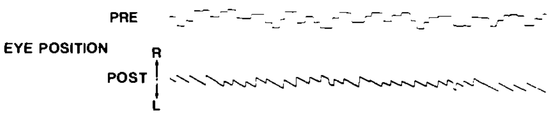
Experiments were performed in 3 adult monkeys (*Macaca fascicularis*)

A- Eye movements were recorded using the search coil technique. The head of the monkey was placed at the center of a servocontrolled turn-table. VOR was tested in the dark using horizontal sinusoidal stimulations (0.02 to 0.15 Hz; 30°/sec). Animals were tested before and after unilateral ablation of cortical area 7.

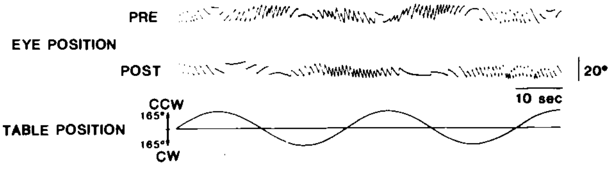
B- At the end of the experiment WGA-HRP (2%) was injected in the intact area 7 on the side opposite to the lesion. Sections were incubated in TMB according to Mesulam (1978) procedure.

RESULTS A :

A UNILATERAL (right) LESION OF PARIETAL CORTICAL AREA 7 IN MONKEYS PRODUCED :

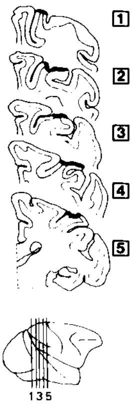


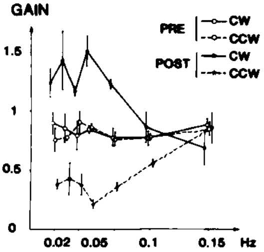
A CLEAR SPONTANEOUS NYSTAGMUS (SN) IN THE DARK.
The fast phase of SN is directed toward the lesion side. SN disappeared in the light (Monkey NANA). (R=right; L=left; PRE=before lesion; POST= after lesion)



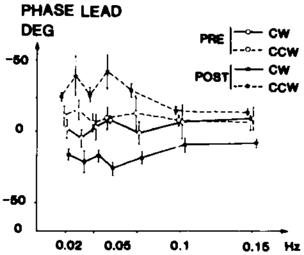
A STRONG VOR ASYMMETRY IN THE DARK WITH GAIN AND PHASE LEAD CHANGES.
VOR recorded in the dark during sinusoïdal table rotation in the clockwise (CW) and counter clockwise (CCW) direction. (0.03 Hz. 30°/sec).(Monkey NANA)

Reconstruction of cortical lesions for monkey NANA. Thick lines on the cross sections and stipped area on the lateral view indicate the zone of lesion.





Mean and standard deviation of VOR Gain and Phase lead in the dark as a function of frequencies for the 2 directions (CW and CCW) of sinusoidal stimulations with a maximum peak velocity of 30°/sec. (Monkey NANA).



VESTIBULO-OCULAR FUNCTION

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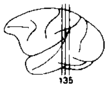
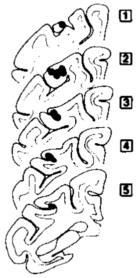
RESULTS B :

AFTER HRP INJECTION IN THE CAUDAL PART OF AREA 7, THE IPSILATERAL VENTRO-POSTERO INFERIOR (VPI) NUCLEUS OF THE THALAMUS IS DENSELY LABELLED.

Reconstruction of HRP injection site in monkey CHLOE.
- On frontal sections, the injection site is in black, the diffusion zone in grey.
- On the lateral view of the brain, the zone of needle penetrations is hatched.





Photograph of the thalamic region with labelled VPI. (Monkey CHLOE)
LD= latero dorsal nucleus; MD= dorso medial N; VPL= ventro postero lateral N; VPM= ventro postero medial N; LGN= lateral geniculate N.

_ Enlarged darkfield photograph of labelled VPI showing the extent of the anterograde labelling↖

_ Light field photograph of VPI: backfield neurons are visible among the labelled terminals.

CONCLUSION

Unilateral ablation of posterior parietal area 7 in monkey induces a spontaneous nystagmus in the dark as well as VOR asymmetry. This asymmetry corresponds to a decrease of VOR gain when the monkey is rotated toward the side contralateral to the lesion with an increase for rotation in the oposite direction. Thjese temporary deficits disappear within a month.

HRP injection in the postero inferior part of area 7 suggest VPI as a possible thalamic relay for vestibular afferents to posterior parietal area 7.

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Grüsser OJ, Pause M, Schreiter U (1982) in:A Roucoux and M Commelinck (eds) Physiological and pathological aspects of eye movements. Junk W, The Hague, pp 251-270.
Kawano K, Sasaki M, Yamashita M (1980) Neurosci Lett 17:55-60.
Kawano K, Sasaki M, Yamashita M (1984) J Neurophysiol 51:340-351.
Mesulam MM (1978) J Histochem Cytochem 26:106-117.

EFFECTS OF BILATERAL FLOCCULECTOMY ON REFLEX (VOR) AND VISUO-VESTIBULAR

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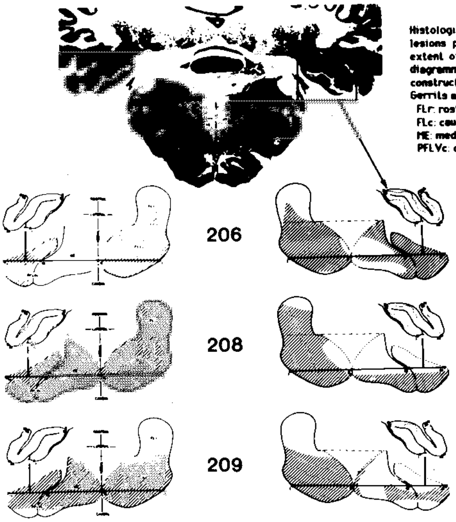
INTRODUCTION

The density of connections between the cerebellar flocculus and the anatomical structures subserving the vestibulo-ocular reflex (VOR) suggests an important participation of the flocculus in the control of eye movements induced by vestibular stimulation. The flocculus receives mainly afferents from primary and secondary vestibular neurons, extraocular muscles proprioceptors and the visual system. In turns, it projects back to the vestibular nuclei. To establish this participation binocular horizontal optokinetic reflex, vestibulo-ocular reflex and visuo-vestibular interactions have been studied in the cat before and after bilateral ablation of the flocculus.

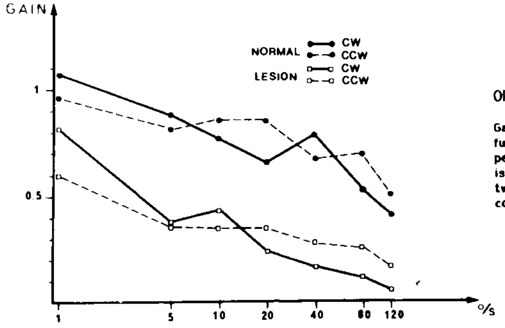
METHODS

Three cats were used in this experiment. Horizontal and vertical eye movements were recorded using the search coil technique. The optokinetic stimulus was a random dot pattern projected on a hemispherical screen at a constant velocity ranging from 1 to 120°/second. The head of the cat was placed at the center of a servocontrolled turntable and horizontal sinusoidal vestibular stimulation (0.02 to 0.32 Hz; =60°/sec) were applied in three conditions: 1) in the dark; 2) with a head-fixed visual field (suppression condition); 3) in front of a sinusoidal optokinetic stimulus with an identical frequency but in opposite direction (out of phase) with a peak velocity value twice that of the vestibular stimulation during one hour (adaptation condition). The animals were tested before and after bilateral flocculectomy performed under visual control through a dissecting microscope.



Histological reconstruction of the three bilateral lesions performed at the level of the flocculus. The extent of each lesion is presented on two dimensional diagrammatic representation of the floccular complex constructed according the technique proposed by Gerrits and Vogd (1982).

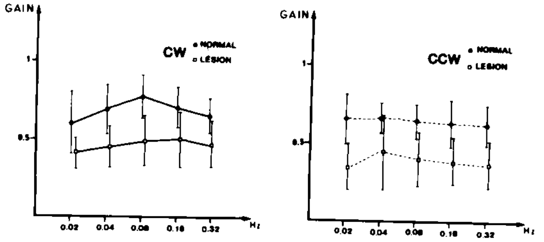
FLr: rostral flocculus
FLc: caudal flocculus
ME: medial extension of the PFLVc
PFLVc: caudo-medial lobule of the ventral paraflocculus



OPTOKINETIC NYSTAGMUS. (OKN)

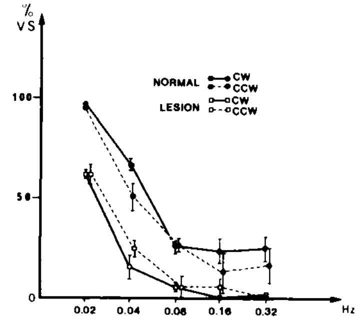
Gain of the horizontal binocular OKN for the cat 208 as a function of the stimulus velocity (from 1 to 120 degrees per second). OKN gain (eye velocity/stimulus velocity) is represented before and after bilateral lesions for the two directions of visual stimulation (CW: clockwise; CCW: counterclockwise).

OPTOKINETIC (OKN), VESTIBULO-OCULAR INTERACTIONS IN THE CAT.



VESTIBULO OCULAR REFLEX (VOR)

Mean and standard deviations of the vestibulo ocular reflex gain in the dark. The values are indicated for the two directions (CW: clockwise; CCW: counterclockwise) of sinusoidal stimulation with a maximum peak velocity of 60°/sec.

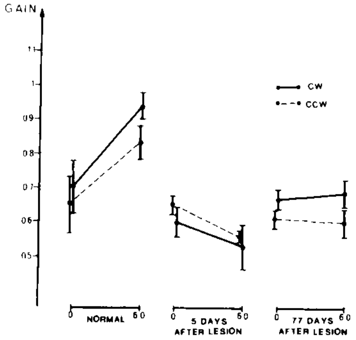


VISUAL SUPPRESSION OF THE VOR

Percentage of visual suppression

$$\left(\frac{\text{gain in the dark} - \text{gain in the light}}{\text{gain in the dark}} \times 100\right) \text{ for cat 209.}$$

100% indicates a total suppression of the VOR when the animal is rotated sinusoidally in front of a head-fixed visual surround. 0% indicates no effect of the visual stimulation. Post operative values are measured four days after lesion.



ADAPTATION OF THE VOR.

The adaptation of the vestibulo-ocular reflex is illustrated for cat 209. VOR gain is measured in the dark at the beginning of the session (time 0 on the abscissa). Then after 60 minutes of visuo-vestibular stimulation, the VOR gain is measured again (time 60 on the abscissa). The values are means of response to 8 cycles of sinusoidal stimulation (0.1 Hz; peak velocity: 25°/sec) for the two directions of stimulation (CW and CCW). In normal animal the VOR gain is significantly higher after one hour than at the beginning of the session. After lesion the possibility of adaptation is lost even after 77 post operative days.

CONCLUSION

As already demonstrated in other species, the flocculus is involved in vestibular and visuo-vestibular processes in the cat. After bilateral lesion of this structure the main deficits are a decrease of horizontal optokinetic reflex gain, a reduction of VOR gain in the dark, a lower ability to supress VOR and a complete loss of the possibility of VOR adaptation. These deficits persist even after three post-operative months, except for visual suppression of VOR.

EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

INTRODUCTION

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The papers in the present chapter on Visual Scanning attempt to understand oculomotor activity when Subjects examine complex scenes or configurations.

Several contributions experimentally test various theoretical questions concerning the precise eye movement mechanisms underlying visual search. The first two papers (by Jacobs and by Nattkemper & Prinz) are attempts to understand what determines eye movement patterns in a simple character-search task: both papers are concerned with the degree of interaction between the temporal and spatial characteristics of eye movements. Jacobs suggests that "where" calculations may be cut short prematurely by "when" decisions. Nattkemper & Prinz show a correlation between saccade size and following fixation duration which they attribute to peripheral preprocessing. A poster by Harris and Hainline concerning eye movements in infants is also relevant to the control of fixation durations: these authors show that fixation duration distributions, like waiting time distributions, are very nearly exponential, suggesting that fixation durations are determined by randomly occurring visual events in peripheral vision. The paper by Rayner & Fisher, like Jacobs and Nattkemper & Prinz, also uses a search task, but is concerned with a sensory rather than an eye-movement control issue: from what zone around the instantaneous fixation point is information being extracted during search?

The remaining papers in this Chapter are not concerned with eye movement mechanisms themselves, and the experiments reported do not test eye-movement related hypotheses. Instead the papers have a more pragmatic approach in which eye movements are used as a tool to understand cognitive processes in various scanning tasks.

Fang, Lüer, Lass & Ulrich study gaze sequences in order to determine the order in which elements in particular spatial arrangements are stored and retrieved, thereby providing evidence for certain types of memorial coding. A similar purpose motivates the paper by Daugs, Blischke & Olivier, who also use eye movements to uncover scanning order, but this time in picture sequences or picture-text combinations that represent gymnastics movements. D'Ydewalle, van Rensbergen & Pollet use eye movement registration to understand why for comfortable reading, subtitle lines in movies or TV should change at certain rates. A poster by Ohlmann, Cian & Mendelsohn shows differences in scanning strategies used by two classes of Subjects doing the Rod and Field test. A poster by Ramsden studies at eye movement tendencies when the Subject looks at a blank screen. Finally a poster by Denoeud is concerned with a different kind of oculomotor activity, namely pupil size changes in short term memory tasks.

Two contributions are concerned with perception of symmetry. In a poster, Pizlo successfully predicts the accuracy with which triangles can be judged asymmetric, by assuming that critical triangle features are distorted by acuity fall-off in peripheral vision. A paper by Locher & Nodine shows that symmetry influences the way the eye scans artwork, fixations being concentrated along the axes of symmetry.

Other work on visual exploration of art is presented by Molnar & Ratsikas, who propose that ergodicity of the transition matrix of successive fixation positions is an index of the quality of a picture's composition. Use of transition matrices appears also in a poster by Pelletier, Grulet & Molnar, which concerns eye movements and texture perception.

A number of contributions are concerned with eye movements in infants or children. Coles' paper, in which infant eye movements are studied in a habituation paradigm, shows up the difficulty of relating eye movements to cognitive behaviour. As Coles points out, this problem, already intractable in adults, is harder still in infants, where maturational changes are taking place continuously over the first few months. Nevertheless, the poster by Mathivet & de Schonen demonstrates cognitive control over eye movements as early as 4 - 11 months, by showing that saccade latencies to familiar faces are shorter than to unfamiliar faces. Finally, as concerns children, two contributions look at the interaction between head and eye movement strategies: the paper by Netchine, Pugh & Guihou, and the poster by Pauchard.

Unfortunately comparatively few of the papers here satisfied our original wish of emphasizing a more theoretical approach to the subject of scanning. In our opinion, progress cannot be made until the basic constraints on scanning imposed by the properties of the oculomotor system are brought into relation with models of the Subject's presumed instantaneous cognitive activity. We hope that at future conferences this will become a reality.

EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

TOWARD A MODEL OF EYE MOVEMENT CONTROL IN VISUAL SEARCH

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At each fixation during visual search and reading the brain must carry out two elementary operations : It must decide WHEN to move the eyes and it must compute WHERE to send them. In this paper experimental data are summarized which indicate that in a simple letter search task these elementary oculomotor decisions depend on cognitive processes based on a representation of the visual properties of the sought-for target. In order to account for these results, a tentative model of the control of exploratory saccades is proposed. The model uses two independent sub-systems for "when" and "where" control and it allows predictions about oculomotor decision times and saccade latencies in letter search tasks as a function of target detectability in peripheral vision.

INTRODUCTION

If we want to understand the mechanisms underlying the control of complex eye movement behaviors, such as in a visual search or reading task, we must analyse the functioning of two elementary operations which the brain must carry out at each fixation during search or reading : It must decide when to elicit the next saccade (the "WHEN"-decision) and it must compute the landing position or amplitude of this saccade (the "WHERE"-decision).

The present paper deals with these problems of when and where to send the eyes at each fixation. In order to tackle these problems a simple letter search task is used involving a scanning strategy just as in reading. Such a simple task allows a clearer analysis of the mechanisms underlying the when and where decisions than a reading situation.

A SIMPLE LETTER SEARCH TASK

Figure 1: Examples of stimulus lines used in the letter search task.

1 - the easy "c" condition; search for a dissimilar target letter having a large visual span:
"xxxxxxxxxxxxxxxxxcxxxxxxxxxxxxxxx"

2 - the difficult "z" condition; similar target letter having a relatively small visual span:
"xxxxxxxxxxxxxxxxxxzxxxxxxxxxxxxxx"

3 - the "no target" condition; 10 out of 15 lines contain no target letter at all:
"xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx"

Consider the following simple letter search task, as illustrated in Figure 1. Subjects must scan 15 lines of x's, from left to right just as in reading, in search for a given known target letter which is hidden at random positions within only 5 of the total 15 lines. Of particular interest for the present analysis will be the *saccades programmed in those lines that contain no target letter at all*, that is saccades programmed while "expecting" the appearance of a certain target letter, without this target being present in peripheral vision at the moment when the saccade is elicited. The subject knows what target letter will be used for the given experimental run, so confusion among possible target letters is excluded. What changes from one experimental run to the next is the graphic similarity between the target letter and the background x's. Thus the detectability of the target letter in peripheral vision is changed, since targets dissimilar to the background x's can be detected further out into peripheral vision than targets similar to the x. A measure of the detectability of each target letter within the background of x's consists in what we call the *visual span*, that is the maximum eccentricity (measured in number of letters around the eye's fixation point) at which a given target letter can be detected within a given background with a certain probability (O'Regan, Lévy-Schoen & Jacobs, 1983).

Figure 2a (see below) gives experimental data obtained by Jacobs (1986b) which show that visual span declines rapidly as target-background similarity increases (from level 1 to 4 ; $F(3,9) = 546.6, p<.0001$). Visual span was measured, in number of letters around the eye's fixation point, in psychophysical experiments using an adaptive automised procedure developed by Humbert & O'Regan (1986). In this kind of task, Subjects had to detect a certain target letter, more or less similar to the letter x, within a line of x's, that appeared on a computer screen for 150 ms. The eccentricity at which the target letter appeared was varied (determined by the psychophysical procedure). We ensured that Subjects kept their eyes on the fixation point during the trial by using a photoelectric eye movement recording technique and having trials where this was not the case automatically rejected by the computer (for more details about the method for measuring visual span see Jacobs, 1986a).

Now let us return to the letter search task. Suppose that the subject is fixating a given position within one of the 15 lines of x's during the search for a certain target letter. Assume that the target letter is characterised by a certain detectability in peripheral vision (visual span). During this fixation the brain must calculate the next landing position of the eye and it must decide when to elicit the saccade. The two problems will be analysed separately.

THE "WHERE"-PROBLEM: TYPE "T" AND TYPE "N" SACCADES

As concerns the operation of calculating the next landing position of the eye in the line, two situations must be distinguished in a task like ours. In the first situation the sought-for target letter is visible in peripheral vision at a given fixation because it falls within the visual span which is characteristic of this target. It is known that in this situation the amplitude of the next saccade is computed proportionally to the retinal eccentricity of the localised target (Kapoula, 1983; Jacobs, 1986b). For reasons of distinguishing the type of saccades occurring in our two possible situations, this first type of saccade, which can be controlled by a retinal error signal, will be called *type "T" or Target-directed saccades*. In the second possible situation the sought-for target is not visible in peripheral vision at a given fixation, either because it does not fall within the visual span or because it is absent in the line just scanned. In this last situation, occurring frequently during a classical scanning task, the "where" of the next saccade cannot be determined on the basis of a simple retinal error signal, because strictly speaking, there is none. This second type of saccade will be called *type "N" or No-target saccade*.

In a recent paper by Jacobs (1986a) the hypothesis was put forward that the calculation of the amplitude of these saccades, programmed in the absence of the sought-for target letter in the line, might depend on the visual span which is caracteristic of this target. The idea behind this "visual span control hypothesis" was that in case of type "N" saccades the eye should be sent to a region of the line where new visual information is expected, that is to the limit of the visual span that the Subject anticipates for the sought-for target (since he or she knows perfectly the detectability in peripheral vision of each possible target letter): If the visual span of the sought-for target is large, type "N" saccades should also be large; if the sought-for target has a relatively small visual span, type "N" saccades should also be small on average.

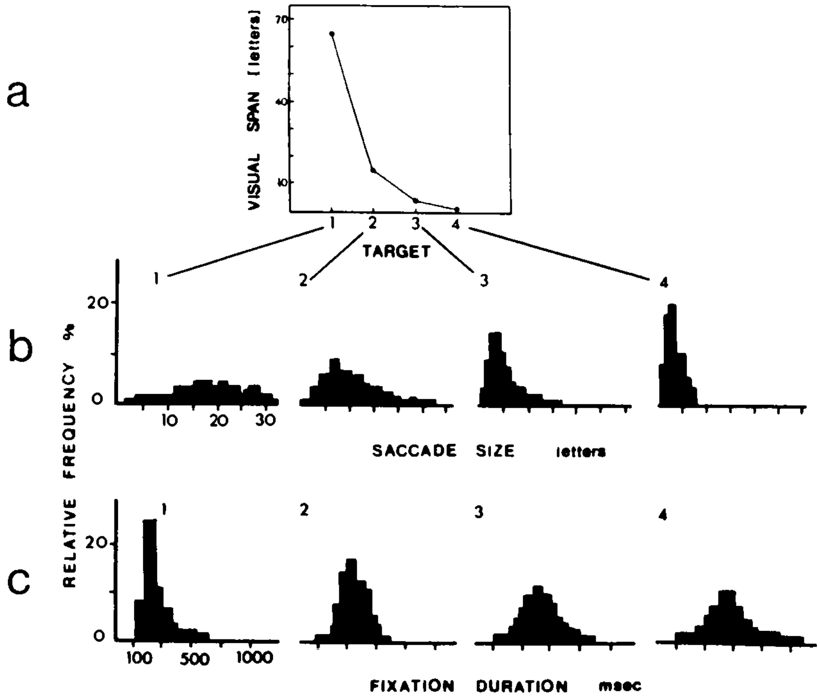

Figure 2: Visual span (a), relative frequency of saccade sizes (b) and fixation durations (c) (cumulated for four subjects) as a function of target-background similarity. The four levels of increasing target-background similarity correspond to the four target letters (in order of increasing similarity): C, c, k' and x'. These targets were chosen using the method of letter similarity estimation proposed by Keren & Baggen (1982). Note that for the two most similar target letters, denoted k' and x' (level 3 and 4) the letter matrices used by the computer were modified. For example, x' means a target which was identical to the background x's, except for one pixel in the upper left half of the matrix. The data summarized in Figure 2 were obtained by Jacobs (1986b). Progression saccade size (in number of letters skipped) and fixation duration (in ms) were measured in a visual search task similar to the one illustrated in Fig. 1. In this search task, the same S's as in the psychophysical experiment mentioned above had to scan 15 lines of x's (of which 5 contained 1 or 2 targets of a single type) in search for the known target

and to report correctly the number of targets that occurred. At the end of each run the Subject's performance was tested and only trials with correct performance were selected for analysis. Subject's eye movements were monitored by a photoelectric scleral reflection technique and eye movement parameters (mean fixation duration and mean saccade size) were analysed as described in O'Regan et al. (1983). Note that *only data coming from stimulus lines which contained no target letters at all were selected for the present analysis*, so in each of the experimental conditions reported in Fig. 2 b and c the retinal information actually was identical, namely lines containing only x's. What changed was the Subject's knowledge about the target letter to search for or his level of uncertainty about the presence of this target letter within the line.

The above mentioned "visual span control hypothesis" is supported by the experimental data summarized in Figures 2a and b. In these Figures it appears clearly that saccades of type "N" (only these were selected for the present analysis) adjust directly to changes in visual span since their average size decreases ($F(3,9) = 110.5$, $p<.005$) when visual span declines as a function of target-background similarity. This result indicates that *type "N" saccades are in effect controlled by cognitive processes based on a representation of the visual properties of the sought-for target letter*. In other terms, the brain uses a memory representation of the sought-for target and its visual span in order to control efficiently the size of saccades programmed in the absence of the target in peripheral vision (Jacobs, 1986a). Our data seem consistent with recent findings by Rayner & Fisher (this volume) and put constraints on models of saccade control: A sensory retinal error signal is not sufficient to account for saccade size control in visual search tasks and a nonsensory control mechanism or channel must be postulated (see Figure 3 below).

THE "WHEN"-PROBLEM: WHAT MIGHT BE THE COGNITIVE EVENT TRIGGERING AN EXPLORATORY SACCADE ?

In order to answer the questions of "when does the eye move at a given fixation during search ?" and "what makes it move just at this moment ?" an analysis of the decision mechanism supposed to trigger a saccade must be done (McConkie, Zola & Blanchard, 1984). What might be the crucial information, in a task like ours, that enables the brain to decide when exactly to trigger the next movement ?

The hypothesis put forward here is simple: It considers that the *cognitive event triggering a saccade in a situation like ours consists in the achievement of a decision about the presence or absence of the sought-for target within the fixated area of the line*. This decision must be elaborated at each fixation because the calculation of the saccade amplitude will be different when the sought-for target is present within the visual span of the given fixation than when it is absent: If the sought-for target falls within the visual span at the given fixation, then the next saccade (a type "T" saccade, following our classification) will be programmed directly on the target, as shown by Kapoula (1983), for example. Thus the saccade amplitude will be proportional to the retinal eccentricity of the localised target. However, if there is no target visible at the given fixation, a type "N" saccade will be programmed, whose amplitude does not depend on retinal information but on a representation of the visual properties of the sought-for target, as shown by Jacobs (1986a).

This assumption concerning the cognitive event triggering a saccade during scanning leads to the following prediction as to saccade latencies (fixation durations): The more background x's and sought-for target are similar, the harder will be the decision, at each fixation during search, about the presence or absence of the target within the visual span. Hence, mean decison time should increase with target-background similarity and so should mean saccade latency.

The data summarized in Figure 2c (see above) are compatible with this view. It is shown that fixation duration (saccade latency) doubles from about 250 ms (condition 1) to about 520 ms (condition 4) when target-background similarity increases ($F(3,9) = 25.4, p < .005$). Note that all these different fixation durations come from physically identical lines, namely lines that contained only x's (only these lines were selected for the present analysis). So the retinal information available at a given fixation was identical across the four conditions and the results cannot be interpreted in terms of sensory effects. What changed was not the retinal information but the Subject's uncertainty about the presence or absence of the sought-for target in peripheral vision within the scanned line (depending on target-background similarity). We also tested if there was a correlation between saccade amplitude and latency which might explain the fixation duration data in terms of a motor effect, but in none of the four experimental conditions we found a correlation coefficient that differed significantly from zero. So it was concluded that this result represents an effect of cognitive factors, namely decisional processes functioning at each fixation in order to determine the presence or absence of the sought-for target letter within the visual span and to calculate an appropriate saccade size (Jacobs, 1986a). In other words, the "when"-decision about the moment of occurrence of a saccade is delayed as a function of the memorized visual properties of the sought-for target.

ELEMENTS OF A TENTATIVE MODEL OF THE CONTROL OF EXPLORATORY SACCADES IN SIMPLE LETTER SEARCH TASKS

In order to deal with the problems of WHEN and WHERE decisions in oculomotor control and to account for the observed data, a simple tentative model is proposed. This model should be considered a first step for throwing a bridge between bio-cybernetic models of the saccadic system that apply to double step task behavior (Becker & Jurgens, 1979; Deubel, Wolf & Hauske, 1984; Robinson, 1975) and recent psychological conceptions about direct and parallel eye movement control in more complex scanning and reading situations (McConkie et al., 1984; Morrison, 1984; Rayner, Slowiaczek, Clifton & Bertera, 1983).

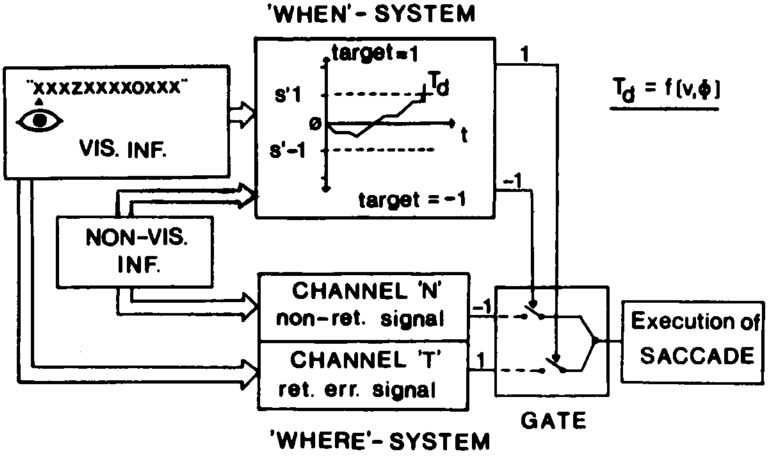

Figure 3: Diagram representing the main hypotheses underlying the tentative model of the control of exploratory saccades.

The model takes up the idea of two independent and parallel saccade control sub-systems (Becker & Jurgens, 1979; Findlay, 1983; Deubel et al., 1984). In addition, it introduces two new concepts as to the possible functioning of these two sub-systems in scanning tasks like the one schematised in Fig. 1. These two concepts are : (1) the idea of two separated channels or mechanisms for amplitude control and (2) the idea that the delay of the "when"- decision is a direct function of the time it takes, at each fixation, to determine the presence or absence of the target within the fixated area of the line.

These two concepts are integrated into the general framework illustrated in Fig. 3. In this Figure it is supposed that visual information activates simultaneously the two classically hypothesized sub-systems involved in eye movement control which are supposed here to function in parallel: The "WHEN"-system which determines the moment of occurrence of a saccade and the "WHERE"-system which prepares the appropriate motor command. In addition, non-sensory information, including knowledge about the sought-for target and its visual properties (its visual span), can also directly influence the oculomotor control sub-systems.

Within the "WHEN"-system a decisional process determines the presence or absence of the target within the fixated area of the line. As a first approximation it is assumed here that the sensory information is accumulated gradually over time by dependent accumulators so that evidence for one possible response is regarded as counterevidence for the other. This decisional process is completed as soon as the sensory evidence for one of the possibilities (target present or absent) prevails and reaches the critical threshold value.

The main hypothesis is now that the two threshold values (s'1 and s'-1) depend on target-background similarity ("v") and that the drift tendency (slope of the function) varies with target eccentricity ("Φ") so that the total oculomotor decision time ("Td") becomes a direct function: $Td = f(v, \Phi)$. For example, for an easy, dissimilar target like the "c" the two threshold values would be nearer to the zero point than for a difficult, similar target like the "z". Moreover, for each of the targets, the slope of the function should be steeper, the smaller the target's eccentricity from the fixation point. This last assumption is based upon experimental data suggesting that the time for sensory encoding increases with retinal eccentricity (Jacobs, 1986b).

Simultaneously, within the "WHERE"-system, each of two separate channels (N and T) prepares the amplitude of the next saccade. Channel "T" on the basis of the spatial visual input or of a retinal error signal (if there is one), channel "N" on the basis of non-sensory information including an internal representation of the detectability in peripheral vision of each sought-for target within the background of x's (Jacobs, 1986a).

According to the outcome of the decision in the "WHEN"-system, a logical "GATE" is opened to one of the two amplitude computation channels that transmits its signal to the saccade execution mechanism. This latter generates the series of neuronal impulses which is sent to the eye muscles.

It is important to note here that *once the when-decision is achieved a saccade will be elicited*, whether the amplitude computation is already accomplished or not. This means that in the case of short decision times (or oculomotor latencies), the spatial parameters of the saccade might not be perfectly prepared, resulting in a saccade which is inaccurately adjusted to its target.

To sum up: The proposed tentative model assumes that the choice between the two independent channels for saccade amplitude control is determined by a decision mechanism, functioning at each fixation. The delay of this mechanism and thus of oculomotor latencies (in tasks like ours) is a function of two visual variables: the graphic similarity between the sought-for target and the background, and target eccentricity. For more details on the model, and on the functioning of the decision mechanism in particular, see Jacobs (1986b).

INTERPRETATION OF THE EXPERIMENTAL DATA IN TERMS OF THE MODEL

It will now be discussed how the model can account for the experimental data summarized in Figure 2.

Amplitudes of type "N" saccades

For the cases where a target falls within the visual span at a given fixation, the spatial parameters of these type "T" saccades are controlled by retinal information (through channel T in our diagram) and directed towards the target. Amplitude and accuracy of these target-directed or type T saccades can be predicted by recent models of the bio-cybernetic type which focus on this special case (Becker & Jurgens, 1979; Deubel et al., 1984) and we will not consider them here.

As concerns the control of the amplitude of type N or "No-target" saccades, we assume in our model that the Subject adapts his or her scanning strategy to the anticipated (memorized) visual span of the sought-for target (e.g. the target is easy or difficult to detect in peripheral vision). This sets the global, maximum gain control (amplitude) for the type N saccades, which are controlled through a separate, non-sensory channel within the "where"-system that has access to a memory representation of the properties of the sought-for target. This means that at each fixation during search where the sought-for target has not been localized in peripheral vision, the Subject will move his or her eyes approximately to the (anticipated) limit of the visual span of the sought-for target letter. As discussed above, the data of Figures 2a and b are entirely consistent with this view.

As to the possible nature of the amplitude control signal it might be speculated that it consists of some sort of mean efference copy associated with the first saccades which are made during the scanning of the first lines (that always contained one or two targets), but this can only be determined with the help of physiological research. What must be emphasized here is the point that our data leave no doubt about the existence and efficiency of a non-sensory control mode of exploratory saccades, justifying the presence of the "N" channel within the model.

Fixation durations

Following the model, oculomotor decision times are expected to change directly as a function of (1) target-background similarity and of (2) target eccentricity. (In this paper only the predictions as to target background similarity and not as to target eccentricity are analyzed, since type T saccades, that is cases where a target falls within the fixated area of the line are not considered here). In particular, target-background similarity should influence, at each fixation, the delay of the "when"-decision because the decision thresholds (criterions) are altered as a function of the knowledge about the sought-for target and its detectability, in the way discussed above (see Fig. 3): The "when"-decision should be delayed the more, the higher target-background similarity and, hence, fixation durations should increase when a more similar target letter is used. The interesting point here is that significant differences in fixation durations are predicted for the scanning of physically identical lines of "x"'s, that is, the lines which contain no target at all. This is in fact what was found, as shown by Figure 2c: Apparently the visuo-motor system hesitates about two times longer at each fixation before eliciting a saccade when a very similar target letter is used (condition 4) than when a dissimilar target is used (condition 1), although retinal information is the same in both cases.

Aiming consistency and precision of type "N" saccades

Another interesting point here is the analysis of the aiming consistency or accuracy of type "N" saccades. The "visual span control hypothesis" claims that at each fixation during scanning, the saccade parameters would be adjusted as accurately as possible to the anticipated visual span of the sought-for target (Jacobs, 1986a). But since it is also claimed in the model that once the "when"-decision is achieved, a saccade is irrevocably elicited, independently of whether the "where"-computation is already accomplished or not, we are lead to the general prediction that the accuracy of saccades should increase, within certain limits, as saccade latency increases, that is, proportional to the "when"-decision delay.

The "aiming accuracy" of type N saccades will be defined with respect to the psychophysical measures of the visual span corresponding to a given target condition. Following the "visual span control hypothesis", the aiming accuracy or consistency of type N saccades can then be evaluated by the degree of variability in saccade sizes as a function of the given target condition and the corresponding visual span: The more saccade sizes are constant in such a task, the better they are adjusted, from one fixation to the next, to the anticipated visual span of the sought-for target.

Figures 2b and c show clearly that the variability of progression sizes decreases dramatically as targets become more difficult to detect (the variance to mean ratios are: 1: 79%; 2: 72%; 3: 56% and 4: 48%), and, as simultaneously fixation durations become extremely long and more dispersed.

This is consistent with the model and can be understood in the following way: When targets are easy to detect in peripheral vision and visual span is relatively large (conditions 1 and 2: dissimilar targets C and c) the "when"-decision time (Td) required at each fixation for determining the presence or absence of the sought-for target within the fixated area of the line is minimal and relatively constant. According to the model, very short "Td"'s might imply that a portion of the saccades are elicited even before the computation of their spatial parameters is accomplished. This should result in inaccurately adjusted saccades. Inaccurately adjusted, however, means in our case that saccade sizes do not well center around a mean value which corresponds approximately to the size of the visual span for the given target condition. As a matter of fact, for easy, dissimilar targets there is no absolute need to adjust each individual saccade accurately to the (anticipated) visual span since the risk to miss a target is minimal. So the S's eyes do not scan a line strictly progressing span by span, but jump rather liberally from one fixation point to the next. The opposite is true in the case of difficult or similar targets (conditions 3 and 4 with targets k and x') where the risk of missing a target is high. As shown in Figures 2b and c we find small and very constant saccade sizes, well centered around the visual span, but extremely long and dispersed fixation durations for these conditions. According to the model, "Td"'s should be very long here leaving enough time for the amplitude computation to be accomplished. So S's seem to adopt a conservative, precise scanning strategy which is time-demanding, moving the eyes rather strictly span by span along the lines (see also Jacobs, 1986a).

This last interpretation concerning the aiming accuracy of saccades as a function of oculomotor latencies is consistent with recent conceptions about parallel programming of eye movements and it offers a parcimonious explanation of the large variability in saccade amplitudes observed in different scanning and reading tasks (see also Rayner et al., 1983; Morrison, 1984).

CONCLUSION

In conclusion, the data discussed in this paper present strong evidence that type "N" saccades in a simple letter search task are controlled by cognitive processes that supplement the sensory analysis of the stimulus material by decisions based upon a representation of the visual properties of the sought-for target. These *decisions intervene in both the computation of saccade amplitudes as well as in determining the moment of occurrence of a saccade* (saccade latencies) (Jacobs, 1986a).

The tentative model presented here integrates several interesting hypotheses about the possible mechanisms underlying these elementary oculomotor decisions in a simple letter search task. The experimental data summarized in Figure 2 are understandable in terms of the model and this is encouraging for further research in this direction. In addition, the model provides a clear, testable assumption about the *cognitive event triggering a saccade* in simple letter search tasks and it takes into account the fact that a non-sensory channel is involved in the control of exploratory saccades. Thus it puts constraints on further theorizing about eye movement control in visual search (e.g. the biocybernetic type of models which only include a sensory control channel for saccade amplitude). Finally, the model allows prediction of oculomotor decision times and saccade latencies from target detectability in peripheral vision for both target directed or type "T" and no-target or type "N" saccades.

Only further research and discussion will allow us to understand if this simple model represents a first step towards the reality of eye movement control processes and/or if it lacks important elements, necessary for reconstructing the complexity of eye movement behavior in visual search.

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SACCADE AMPLITUDE DETERMINES FIXATION DURATION: EVIDENCE FROM CONTINUOUS SEARCH[1]

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We address the issue of the relationship between temporal and spatial decisions of the eye movement control system with respect to a continuous visual search task. Our results suggest that saccade amplitude is independent of the duration of the preceding fixation whereas saccade amplitude partially accounts for the duration of the succeeding fixation. An explanation of these findings is offered, based on the assumption that saccade amplitude determines the degree to which information processed on a given fixation has been preprocessed on the preceding fixation.

INTRODUCTION

The control of eye movements is usually considered to involve two kinds of decision, a temporal decision and a spatial decision. The temporal decision refers to the duration of fixations. It determines when to move the eyes from one location of the display to another. The spatial decision refers to the amplitudes of saccades. It determines where to move the eyes.

Some controversy has centered on the issue of the relationship between temporal and spatial decisions. More exactly, it seems reasonable to assume some relationship between the durations of fixations and the amplitudes of saccades following them. The longer the duration of a given fixation is, the more elements to the left and right of the fixation location can be processed or partly processed. This might lead to an increase in the amplitude of the succeeding saccade. Correspondingly, one would expect to find a substantial correlation between the durations of fixations and the amplitudes of saccades following them. In reading tasks, however, this pattern of results has not been found.
It also seems reasonable to assume a relationship between the durations of fixations and saccade extents, such that the larger the amplitude of a saccade is, the smaller is the overlap between the information processed (or preprocessed) during the two fixations before and after the saccade. This might result in a prolongation of

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fixation time of the second fixation. According to this view one would expect a positive correlation between saccade amplitudes and fixation durations for succeeding fixations. In reading tasks this pattern of results has not been found either.

The fact that substantial correlations between fixation durations and the saccade amplitudes following or preceding them have not been observed, usually stands as evidence for modelling the eye movement control system such that there are two generators which independently select saccade amplitude and fixation duration from their respective distributions (Andriessen & deVoogd, 1973; Rayner & McConkie, 1976; McConkie, 1983; Rayner, 1984).

However, there is at least one experimental observation which casts some doubt on the independency assumption. Kapoula (1983), using a highly simplified digit reading task, found positive correlations between the size of saccades and subsequent fixation durations. This result can be taken as an indication that there may be some correlations between the spatial and temporal decisions of the control system which, for some unknown reasons, cannot be shown in reading tasks.

The range of possible models of the relationship between fixation times and saccade amplitudes is clearly limited. If we assume that there is some local interplay between temporal and spatial decisions, positive correlations could, in principle, be obtained in each of two directions. (i) The larger the amplitude of a saccade, the longer should be the fixation time needed or (ii) the longer the fixation duration, the larger should be the saccade amplitude that the system can afford.

Each of these two correlations would make sense in itself. Note, however, that they cannot be combined. If combined they form a positive feedback loop that would keep building up fixation durations and saccade amplitudes. A long fixation duration would result in a large saccade amplitude, resulting in a longer fixation duration and in turn, resulting in a larger amplitude etc.

Instead two types of correlation patterns seem to be possible. First, one of the correlations might be positive, and the other negative. In this case a negative feedback loop would be installed to prevent building up. If this were correct one should expect negative autocorrelations between succeeding amplitudes or succeeding fixation durations.
Second, one of the two correlations might be positive and the other zero. Such a pattern of results would imply that the two generators are not independent. If we observe positive correlations between saccade amplitude and succeeding fixation duration, this would imply that the saccade amplitude generator which selects saccade size from its respective distribution is independent of fixation time whereas fixation duration partly depends on saccade amplitude. The inverse result - positive correlation between fixation duration and succeeding saccade amplitude combined with zero correlation between saccade amplitude and succeeding fixation duration - would suggest that the fixation duration generator is independent of saccade amplitude whereas saccade amplitude depends on fixation duration.

We studied correlations between fixation durations and saccade amplitudes in a continuous visual search task. This task requires the Subject to scan search lists that were made up of sequences of letters and to search for a predefined target letter which was inserted only once in each list. In our experiments the search lists were arranged in horizontal lines of equal length, and the Subjects were instructed to scan the lists 'as in reading' - line by line and from left to right within each line - and to do so as fast as possible (an example of a search list we used in our experiments is shown in Figure 1).

VTHFVNKLXVFWLTFKMTWHKTKVVLTKKWHXKTXW
FMLFMMFLLTKXHMWHXTWNNHTWTFNNXMVMLHMK
MKWLFNFHVVKKXHMMLVTWXTLTLXFVFWNNMWFL
MLTNTLHWHLLTHLHLKMHTXLFMVKVTWDXLNFLV
XMNTXNTHFHKMTWXXTHXHHKNWHLKHHFMLNNXT
XKLLFLWLWXHTXXNTWFNKMFWTFHXHXFMKKXKN
FXFVXKNHKKNXTNKLVTFHKNVKXLWLTWFFXNXH
XMNTXNTHFHKMTWXXTHXHHKNWHLKHHFMLNNXT
XKLLFLWLWXHTXXNTWFNKMFWTFHXHXFMKKXKN
FXFVXKNHKKNXTNKLVTFHKNVKXLWLTWFFXNXH
VTHFVNKLXVFWLTFKMTWHKTKVVLTKKWHXKTXW
FMLFMMFLLTKXHMWHXTWNNHTWTFNNXMVMLHMK
XMNTXNTHFHKMTWXXTHXHHKNWHLKHHFMLNNXT
XKLLFLWLWXHTXXNTWFNKMFWTFHXHXFMKKXKN
FXFVXKNHKKNXTNKLVTFHKNVKXLWLTWFFXNXH
XMNTXNTHFHKMTWXXTHXHHKNWHLKHHFMLNNXT
XKLLFLWLWXHTXXNTWFNKMFWTFHXHXFMKKXKN
FXFVXKNHKKNXTNKLVTFHKNVKXLWLTWFFXNXH
VTHFVNKLXVFWLTFKMTWHKTKVVLTKKWHXKTXW
XMNTXNTHFHKMTWXXTHXHHKNWHLKHHFMLNNXT
FXFVXKNHKKNXTNKLVTFHKNVKXLWLTWFFXNXH

Figure 1

Example of a search list used in the experiments.

Thus we created a situation that provoked an eye movement scanning routine similar to reading and at the same time avoided the problems that arise when the material to be read has a linguistic and semantic structure.

During the scan we recorded the horizontal component of the EOG in order to identify saccades and times of fixation (for the details of data acquisition and saccade detection algorithms see Nattkemper, Halpaap & Prinz, 1985).

RESULTS

In order to find evidence in favor of one or the other of the alternatives, we analyzed the data of 24 Subjects who participated in five experiments originally planned to assess the effects of redundancy on search performance (Nattkemper & Prinz, 1984; Prinz & Nattkemper, 1985). As a first step we pooled the data of each Subject over experimental conditions (two types of search lists: random and redundant) and sessions (four sessions per Subject) and computed the correlation coefficients (Pearson product-moment-correlation) between fixation durations (with a range from 64 - 1286 ms) and the amplitudes of preceding and succeeding saccades (with a range from 1 - 34 letter spaces, corresponding to .5 - 17 degrees).

The correlation coefficients were based on 2000 - 5000 fixation-amplitude pairs per Subject. The results are shown in Table 1.

Table 1: Correlation (Pearson product-moment-correlation) between fixation durations and the amplitudes of saccades following (FIX → AMP) and preceding (AMP → FIX) fixations.

Subject	FIX → AMP	AMP → FIX
18	-.04	.22
19	-.04	.21
10	.07	.21
14	.08	.19
15	.10	.19
1	.01	.18
21	.06	.16
20	-.10	.15
23	-.04	.13
2	-.03	.11
5	.07	.11
7	.01	.11
17	-.09	.10
6	.01	.08
8	.08	.08
4	.13	.08
24	-.06	.07
11	-.03	.04
13	-.02	.04
3	.02	.03
22	.00	.03
16	.04	.02
9	.06	.01
12	-.10	-.01

Two features of the results are obvious:
(1) In some Subjects we did observe substantial correlations between saccade amplitudes and the durations of succeeding fixations. 17 out of 24 Subjects showed significant positive correlation coefficients.

(2) Concerning the relationship between fixation durations and the extent of subsequent saccades the results were ambiguous. In 6 Subjects we found significant positive correlation coefficients. In 3 Subjects we observed a negative correlation. 15 Subjects did not show any correlation at all.

One might suspect that the observed correlations are due to an artefact. Suppose that Subjects increase both saccade amplitudes and fixation durations during practice (over sessions) and/or that they are both longer in one of the two conditions as compared to the other one. If this were correct the observed correlations were artificially produced by our procedure of pooling the data over sessions and conditions. To make sure that the correlations do not represent an artefact of this kind we also computed correlation coefficients on the basis of fixation-saccade pairs within each of the 2 x 4 = 8 conditions x sessions combinations.

To give an indication of the results we obtained the medians of these coefficients per Subject. These are given together with the individual range of the correlation coefficients in Table 2.

Table 2: Medians and ranges over 8 conditions of individual correlation coefficients between fixation durations and subsequent saccade amplitudes (FIX → AMP) and saccade amplitudes and subsequent fixation durations (AMP → FIX).

Subject	FIX → AMP		AMP → FIX	
	Median	Range	Median	Range
18	.08	-.02 - .14	.23	.11 - .27
19	-.05	-.18 - .01	.25	.11 - .28
10	.07	-.04 - .13	.20	.11 - .28
14	.11	.03 - .16	.17	.01 - .54
15	.19	-.01 - .23	.13	.05 - .30
1	.01	-.28 - .13	.19	.01 - .24
21	.06	-.02 - .09	.18	.08 - .22
20	-.04	-.10 - .07	.17	.13 - .21
23	.03	-.10 - .09	.18	.01 - .29
2	.01	-.12 - .20	.10	-.11 - .30
5	.09	.05 - .11	.03	.01 - .31
7	.02	-.06 - .11	.09	.03 - .40
17	-.01	-.05 - .10	.12	.06 - .15
6	.02	-.06 - .19	.04	-.11 - .13
8	-.02	-.05 - .35	.07	-.12 - .30
4	.11	.02 - .23	.05	.01 - .15
24	.08	-.13 - .18	.12	.00 - .21
11	-.01	-.13 - .03	.02	-.16 - .12
13	-.03	-.12 - .08	.07	-.10 - .13
3	.02	-.01 - .06	.03	-.06 - .11
22	-.02	-.05 - .05	.06	-.08 - .14
16	.06	-.05 - .15	.03	-.02 - .11
9	.09	-.03 - .11	.02	-.07 - .13
12	.02	-.03 - .09	.14	.03 - .19

With regard to the relationship between saccade amplitude and succeeding fixation duration, all of these median correlations were positive and usually did not differ markedly from the overall coefficients (an exception is Subject 12). Moreover, 15 Subjects consistently showed positive coefficients in all local subsets of their data. In 9 Subjects there was some inconsistency, which was not systematically related to experimental conditions or sessions. They showed negative coefficients in some of their local subsets. Yet, as indicated by the positive sign of the median, there were always more positive than negative correlations.

With regard to the relationship between fixation durations and subsequent saccade amplitudes the situation remained ambiguous. Only three out of 24 Subjects (Subject 4, 5, 14) showed positive correlations consistently. In the majority of Subjects we found both negative and positive coefficients in local subsets of the data. The high degree of inconsistency within and between Subjects seems to rule out the assumption of a close relationship between fixation durations and the amplitudes of succeeding saccades.

In summary the results show that substantial correlation coefficients are present not only in the pooled data but in local subsets as well. Moreover, the overall pattern of results suggests, that the relationship between temporal and spatial aspects of saccadic eye movements is such that the saccade amplitude generator is independent of fixation time whereas fixation duration partly depends on preceding saccade extent. This conclusion is further supported by the nonexistence of substantial negative autocorrelations between the durations of successive fixations or the amplitudes of succeeding saccades, thus excluding the possibility of a negative feedback loop to be installed.

To illustrate our findings we performed the following computation: The individual distributions of saccade amplitudes were subdivided in deciles thereby generating ten sets of saccade-fixation pairs. For each of these sets the mean amplitude of the saccades and the mean duration of the fixations that followed these saccades were obtained, yielding ten saccade amplitude/fixation duration pairs for each Subject.

Typical examples illustrating the correlation between saccade size and subsequent fixation duration are shown in Figure 2. Figure 2a gives the data of 4 Subjects who consistently showed positive correlations between saccade amplitude and succeeding fixation duration.

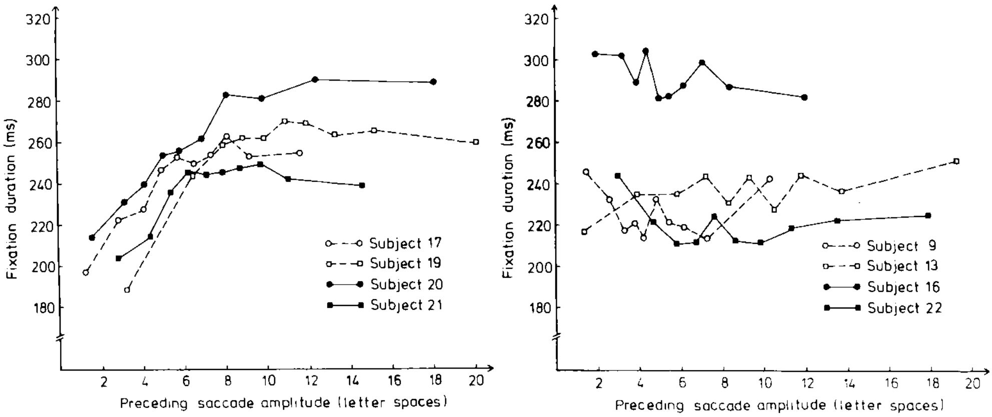

Figure 2

Fixation durations (ms) as a function of preceding saccade amplitudes (letter spaces). (2a) 4 Subjects with high correlation, (2b) 4 Subjects with low correlation.

The inspection of this Figure indicates, that quadratic curves might provide a better fit than a straight line. To check this, we performed tests for linear and quadratic trends (Winer, 1962; pp 132-134) for each of those Subjects who consistently showed positive correlations between saccade amplitude and succeeding fixation duration. In 12 out of 15 Subjects the quadratic trend added significant predictability ($p < .05$) to that given by the linear trend. In these

Subjects fixation durations seemed to increase monotonically with saccade amplitudes in the range from approximately 1 to 8 character spaces (corresponding to .5 to 4 degrees). Yet, fixation duration seemed to become independent of the amplitude of the preceding saccade when the eye is pushed into more remote regions.

Figure 2b illustrates the results of 4 typical Subjects who showed no substantial correlations between saccade size and succeeding fixation durations. These curves show that in these Subjects there is not only no linear relationship, but no indication of a nonlinear relationship as well: fixation durations are virtually independent of preceding saccade amplitudes.

DISCUSSION

Our results support the assumption of some (admittedly weak) local interplay between the spatial and the temporal decisions of the eye movement control system. The saccade amplitude generator which selects saccade size from its respective distribution, seems to be independent of preceding fixation time whereas fixation duration is weakly dependent on the amplitude of the preceding saccade.

The explanation of these findings may be based on the idea that the degree of preprocessing partially determines the time needed to identify the elements encountered on a given fixation. We assume that there is a control area around the fixation location from which different kinds of information can be obtained. Information from foveal and near parafoveal vision leads to letter identification; more gross types of information - presumably visual feature information - are obtained further into the periphery around the fixation location (Prinz, 1985). If one further assumes that the partial information from noncentral vision can be integrated across saccades, one should expect that saccade amplitude determines the degree to which information processed on a given fixation has been preprocessed on the preceding fixation. The larger the amplitude of a saccade, the smaller is the overlap between the information processed or preprocessed during the two fixations before and after a saccade. The smaller the overlap between the information from two successive fixations, the weaker is the priming effect resulting from preprocessing during the preceding fixation. This, in turn, leads to an increase in the time needed to identify the elements encountered on the second of the two fixations.

Our finding that fixation durations tend to reach an asymptote for saccade amplitudes larger than about 8 character spaces is well in line with this explanation. As is known from studies of the effective visual field in reading, the region from which rather detailed visual information can be obtained seems not to exceed seven letters to the right of the fixation location (O'Regan, 1980; McConkie, 1983). Further to the right only gross types of information are acquired which cannot facilitate letter discrimination on the following fixation.

In conclusion, our findings, as well as those of Kapoula (1983), cast some doubt on the assumption that saccade length and fixation duration are independently controlled (Rayner & McConkie, 1976; Pollatsek & Rayner, 1982). The finding of zero correlations between these parameters with respect to reading might be due to the dominance of linguistic processing, which, as a major contributor to fixation duration, overrides more elementary contributors.

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EYE MOVEMENTS AND THE PERCEPTUAL SPAN DURING VISUAL SEARCH

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Subjects searched for a target letter in arrays consisting of visually similar or dissimilar letter distractors. A window moved in synchrony with their eye movements and how much information was available for processing on each fixation was controlled. The results of the experiments indicated that the size of the perceptual span in the search task was very similar to the size of the perceptual span in reading. Further results indicated that 3-6 letters were identified per fixation while 12-16 letters received some type of processing. Similarities and differences between the search task and reading were discussed.

INTRODUCTION

Since Neisser's (1964) classic work in which subjects searched for the presence or absence of a target letter in an array, numerous studies have been conducted to understand the basic processes involved in visual search. Our goal in the research described here was to adopt the moving window paradigm introducted by McConkie and Rayner (1975) and widely used to study the size of the perceptual span in reading (see Rayner, 1984 for a summary) to study visual search. The perceptual span can be defined as the area from which subjects obtain useful information during an eye fixation. We were particularly interested in the size of the perceptual span when subjects are searching an alphabetical array rather than reading. In reading, the perceptual span extends from 3-4 character spaces to the left of fixation to 15 character spaces to the right of fixation (Rayner, 1984). We were interested in the extent to which the perceptual span in visual search might differ from or be similar to the perceptual span in reading.

In the experiments, subjects were asked to search for a target letter in a row of other letters as their eye movements were recorded. Wherever the subject looked, a window moved in synchrony with the eye movements. Around the fixation point, within the window region, all of the characters from the stimulus array were available for processing. However, outside of the window, the characters were replaced by other irrelevant characters. For example, outside of the window area all of the letters from the search array were replaced with Xs. Thus, in Experiment 1 we were able to investigate the size of the perceptual span (or area of useful vision) in our search task and in Experiment 2 we were able to control the number of letters that were available for processing on each eye fixation. The paradigm thus allows subjects to move their eyes freely while the experimenter is able to control how much information is available for processing.

The basic assumption in the research was that when fewer letters are available within the window for processing than the subject can efficiently process during a fixation, search will be slowed down. Conversely, when as many letters as can be processed on a given fixation are available, search performance will not differ from a control condition in which no window is presented (i.e., the entire array is available for processing).

Since numerous experiments have been conducted using the moving window technique to study reading, we hoped to make some comparison between reading and visual search. It is often argued that visual search and reading are related and if we could understand the processes involved in visual search, it may elucidate processes involved in more complex tasks like reading (cf., Crowder, 1982). Recent research by Jacobs (1986) and by Levy-Schoen, O'Regan, Jacobs, and Coeffe (1984) has focused on the relationship between the visibility span and eye movements in a search task. Part of the goal of that research appears to be to delimit the range over which target letters embedded in other letters can be discriminated. Such work has clear relevance to the reading process and our work is somewhat similar to theirs. However, in our experiments, unlike theirs, a window moved in synchrony with the eyes.

EXPERIMENT 1

In Experiment 1, four highly practiced subjects searched for the letter b or y. On half of the trials the target was present while in the other half of the trials it was absent. Within any one trial block, subjects searched for only one of the targets. There were eight blocks of 120 trials. Each session began with 40 practice trials and all of the subjects were practiced in the task before the experiment began.

Letter strings consisting of 24 letters arranged horizontally were used as stimulus arrays. The 24 letters were divided into four string lengths of 2, 4, 6, or 8 letters per string. Thus, a given stimulus array consisted of either twelve 2-letter strings, six 4-letter strings, four 6-letter strings, or three 8-letter strings. When the target letter was present in the array, its location in the array was randomly determined. In addition to varying the string size, we also varied the size of a window that moved in synchrony with the subject's eyes. The size of the window was either 7, 13, 19, 25, or 31 characters around the fixation point. In addition, a control condition was included in which the array was presented normally without any restraining window (no window condition). A window size of 13 characters meant that 6 character spaces to the left and right of fixation were available for processing. Outside of the window area, all letters and spaces were replaced by Xs. Table 1 shows an example window on two consecutive fixations.

Table 1

Sample stimulus arrays from Experiments 1 and 2.
Examples include two consecutive fixations (marked by the dot).
The example for Experiment 1 consists of a similar background
while that for Experiment 2 consists of a dissimilar background.

Window Size	Experiment 1	
No Window	pqjp qjpg pqjp pyqj pqjg gpjq	
13	XXXXXqjpg pqjp pyqjXXXXXXXXXX	n
	XXXXXXXXXXXqjp pyqj qpjgXXXXX	n+1
	Experiment 2	
No Window	wvsc scvw vwcs sywv vwsc vvwc	
2S	XXXX scvw vwcs XXXX XXXX XXXX	n
	XXXX XXXX vwcs sywv XXXX XXXX	n+1

Note: Fixation sequence is indicated by n and n+1.

The similarity of the distractor letters to the target were also systematically varied. When b was the target letter, visually similar arrays consisted of the letters h, k, d, and l. When y was the target letter, the visually similar arrays consisted of the letters g, j, q, p. The dissimilar arrays consisted of the letters v, s, c, z, r, w, and n.

The letter strings were displayed on a Hewlett-Packard 1300A cathode ray tube (CRT), which has a P-31 phosphor with the characteristic that removing a character results in a drop of 1% of maximum brightness in .25 ms. The letters were printed in lower case on the CRT. A black theatre gel covered the CRT so that the letters appeared clear and sharp to the subjects.

Eye movement recording was accomplished by using a Stanford Research Institute Dual Purkinje eye tracker, which has a resolution of 10 min of arc and a linear output over the visual angle (8-12 deg) occupied by the letter strings. The eyetracker and the CRT were interfaced to a Hewlett-Packard 2100 computer that controlled the experiment. The signal from the eye tracker was sampled every millisecond and the position of the eye was determined every 4 ms. The display change associated with each eye movement was accomplished within 5 ms of the completion of the saccade. The computer kept a complete record of the duration, sequence, and location of each fixation.

In the experiments, the subject's eye was 46 cm from the CRT and three characters equaled 1 deg of visual angle. Eye movements were recorded from the right eye, although viewing was binocular. Luminance on the CRT was adjusted to a comfortable level for the subjects and the subjective brightness was held constant throughout the experiment. The room was dark, except for a dim indirect light source. More details about the apparatus are described by Rayner, Inhoff, Morrison, Slowiaczek, & Bertera (1981)and Rayner, Well, Pollatsek, & Bertera (1982).

The primary dependent variable in both experiments reported here was search time expressed as processing time (in milliseconds) per character. There was no difference in search time for the two target letters. Also, a comparison of the search time for positive (target present) and negative (target absent) trials revealed no difference between the two conditions. However, there was considerably more variability in search times for positive than negative trials, due primarily to the location of the target. Hence, search times for trials in which the target was absent will be used in the data analyses to be reported. Errors were very rare in both experiments; the error rate did not exceed 1.3% of the trials. There were no indications of any speed-accuracy trade-offs. Subjects were instructed to search as rapidly as possible without making any errors and the resulting data clearly indicated that they were able to do this.

Figure 1 shows the search time as a function of the type of distractor letters and Figure 2 shows the search time as a function of string size. From these figures it can clearly be seen that type of distractor had more of an influence on performance than did the density of the arrays (since string size can be characterized as specifying how tightly packed the array was). While there was clearly an effect of string size so that arrays consisting of two letters per string were searched more slowly than other sized arrays, most of the effect was due to the fact that subjects made shorter saccades in this condition. This result is consistent with findings reported previously suggesting that the tendency to fixate the object closest to fixation is very coercive (Engel, 1977; Levy-Schoen, 1974). In the condition in which confusable letters were present in the background, subjects were very influenced in how far they moved their eyes by the length of the string and tended to move to the next string seldom skipping over a string.

Figure 3 shows the number of fixations per array, the average fixation duration, and the average saccade length as a function of the type of background distractor and the window size. From the three figures it is clear that asymptotic levels of performance were reached when the window was 25 character spaces (confusable background) to 31 character spaces (non-confusable background). The point at which the performance reached asymptote is very similar to the size of the perceptual span in reading. In a subsequent experiment, we also found that, as in reading, the perceptual span in our search task was asymmetric to the right of fixation. Subjects in the search task (as in reading) appear to obtain information no more than three or four letter positions to the left of fixation. This was ascertained by restricting the size of the window to the left of fixation. When the left-hand boundary of the window began three letter positions to the left of

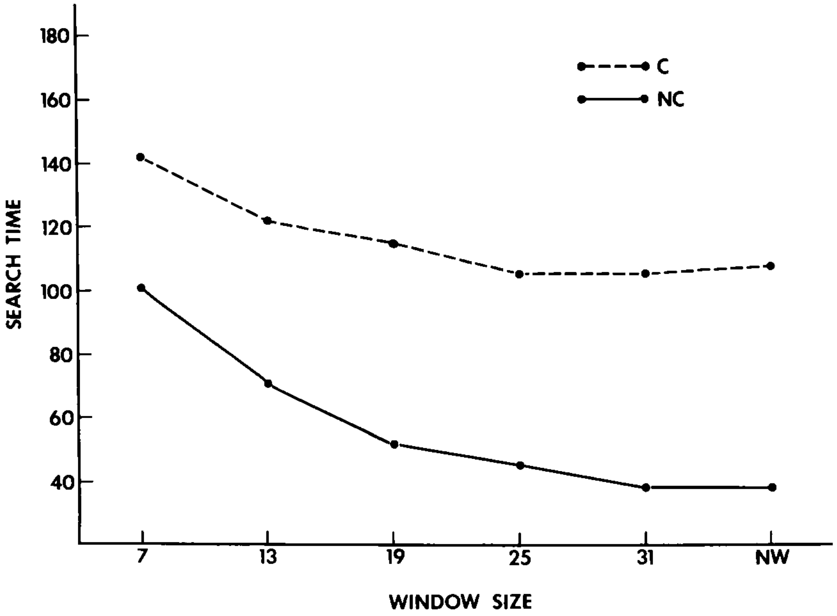

Figure 1
Search time (milliseconds per character) as a function of window size and background distractors.
C = confusable background; NC = non-confusable background.

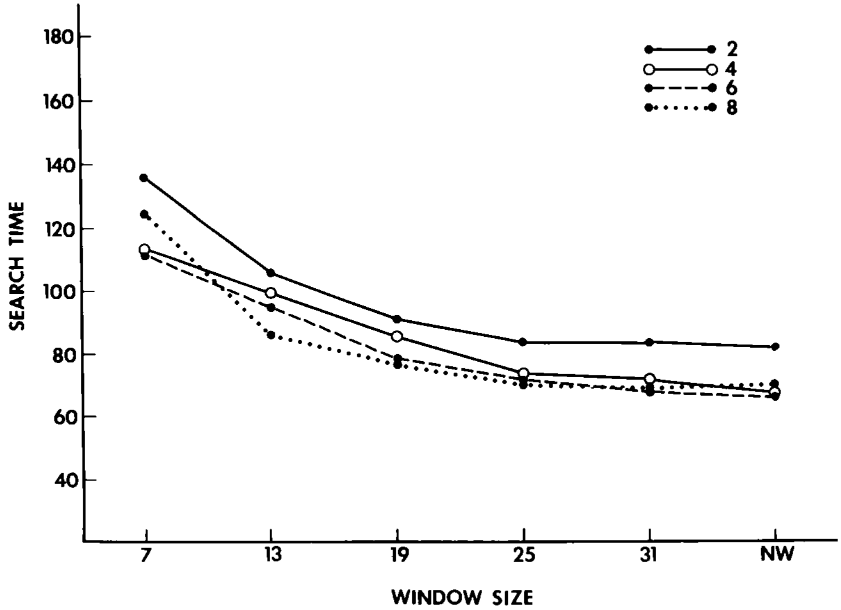

Figure 2
Search time (milliseconds per character) as a function of window size and string size.

fixation, search was only slightly slower than when the window began much further to the left and when it began four letter positions to the left of fixation, search did not differ from when the window began further to the left. Furthermore, except for string size 2 subjects seemed to obtain useful information to the left of fixation only from the beginning of the currently fixated string. In short, our estimate of the perceptual span ranges from 16 character spaces (25 ÷ 2 = approximately 12 characters to the right plus four character spaces to the left) to 19 character spaces.

While Experiment 1 provided information about the size of the perceptual span when subjects are searching for a specified target letter, we were not able to control exactly how much information was available to the subject in as precise a manner as we would like. Experiment 2 was thus carried out to control exactly how many letters were available for processing per fixation.

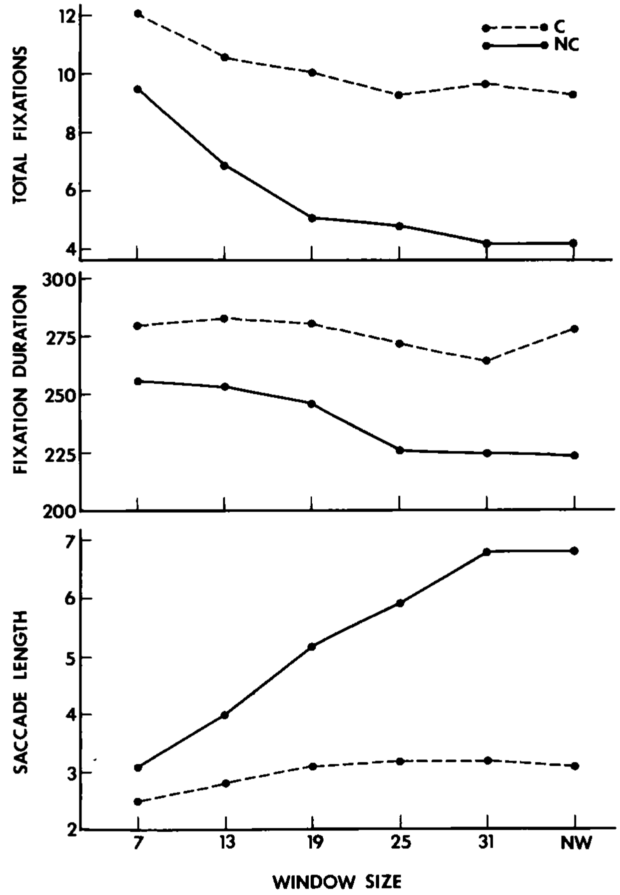

Figure 3
Total fixations, fixation duration (in milliseconds), and saccade length (in character spaces) for left-to-right saccades as a function of window size and background.
C = confusable background
NC = non-confusable background

EXPERIMENT 2

Four highly practiced subjects participated in the experiment. As in Experiment 2, they were asked to search for the target letter b or y. All of the apparatus and procedures from Experiment 1 were identical except that the characteristics of the window differed in Experiment 2. In Experiment 2, the window corresponded to string boundaries and all of the spaces between strings were preserved outside of the window area. In the 1S condition, only letters from the currently fixated string were available with all other letters replaced with Xs. In the 2S condition, all letters in the currently fixated string were available, as were all letters in the string immediately to the right of fixation. In the 3S condition, all letters in the currently fixated string were available, as were all letters in the two strings to the right of fixation. Finally, in the NW (no window control) condition, the entire array was presented normally without any window constraint. Table 1 shows sample strings on two consecutive fixations.

Figure 4 shows the search time as a function of the type of distractor letters and Figure 5 shows the search time as a function of string size. As is clear in Figure 4, background characteristics had a major effect on search performance.

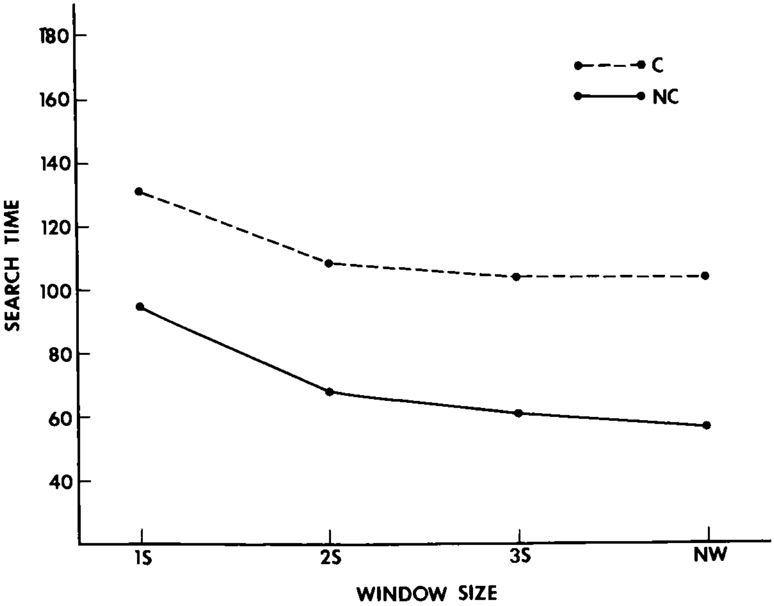

Figure 4
Search time (milliseconds per character) as a function of window size and background distractors.
C = confusable background; NC = non-confusable background.

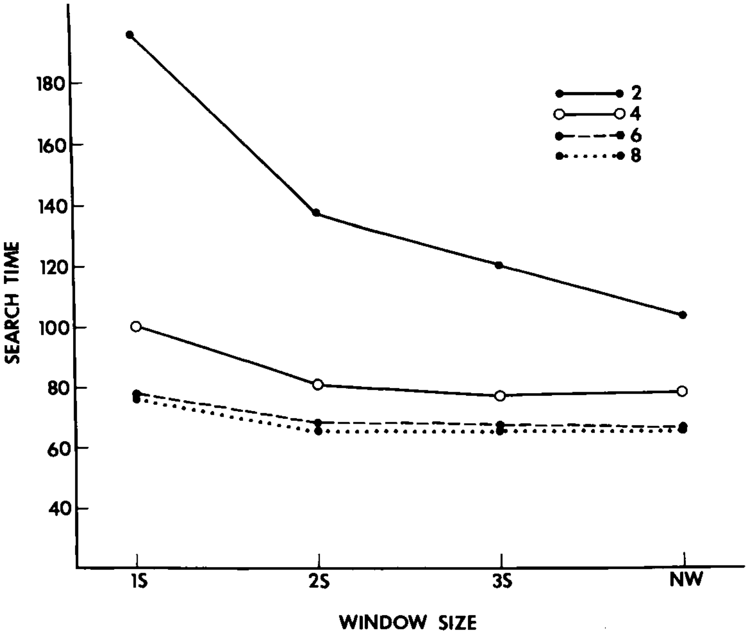

Figure 5
Search time (milliseconds per character) as a function of window size and string size.

From Figure 5 it can be seen that search was slower when the string size was 2 letters than when it was 4 letters, which in turn was slower than string sizes of 6 or 8. These latter two conditions did not differ from each other. Figure 6 shows the eye movement data from the experiment. In order to facilitate comparison with Experiment 1, we have collapsed across string size.

From the figures it is clear that performance reached asymptotic levels for string sizes 4-8 when the window included two strings. This result is quite consistent with the results of Experiment 1. However, in Experiment 2 our primary interest was to specify the number of letters that could be processed per fixation. There are two ways to go about estimating the number of letters that are processed per fixation. First, if we make the simple assumption that saccade length represents the number of letters that have been processed on the prior fixation, then we would estimate that 3-6 letters are processed per fixation. Perhaps saccade length reflects the number of letters that have been identified (at least to the level that the subject knows that the letters are not the target) on the prior fixation. Examination of the length of the saccade to the target (or close to the target) in those cases when a target was present in the display revealed that its average length did not differ appreciably from the mean saccade length when a target was not present. This latter fact reinforces the assumption that saccade length reflects the number of letters that have been identified and the subject simply moves to the next unidentified letter on each saccade. If we accept this line of reasoning, then it would appear that fewer letters are identified when the distractors were similar to the target (about 3-4 letters) than when they were dissimilar (5-6 letters).

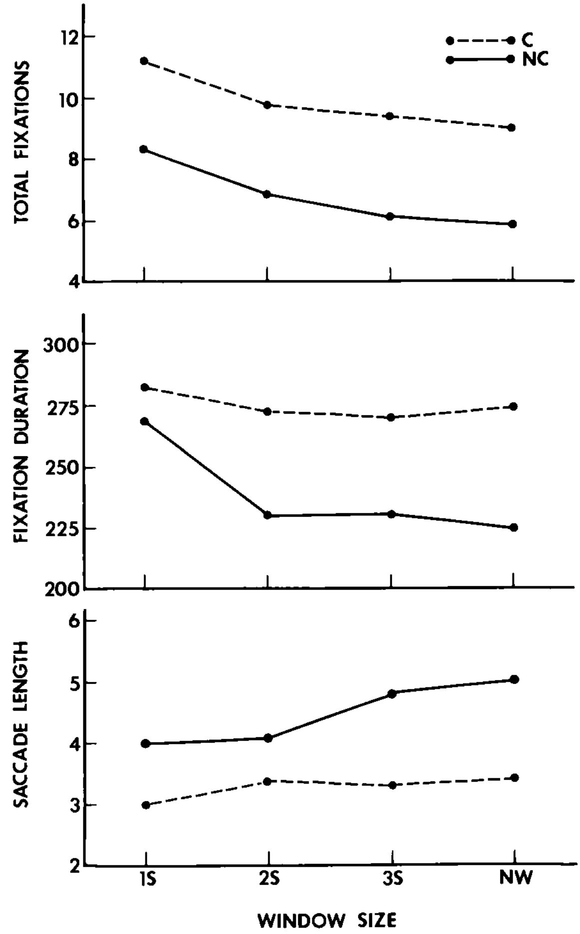

Figure 6
Total fixations, fixation duration (in milliseconds), and saccade length (in character spaces) for left-to-right saccades as a function of window size and background
C = confusable background
NC = non-confusable background

A second way to estimate the number of letters that have been processed involves examining search time solely as a function of the number of letters from the array that were available per fixation. This procedure involves collapsing across window size and string size. Although not evident in the Figures because we collapsed across window size and string size, the data revealed that 12 letters received some type of processing when the distractors were similar to the target.

However, when the distractors were dissimilar to the target, up to 16 letters received some processing. As can be seen in Figure 5, there was little difference between string sizes 6 and 8 for any of the window sizes used.

DISCUSSION

The experiments reported here were designed primarily to investigate the size of the perceptual span when subjects are searching for a target letter and to determine the number of letters that are processed per fixation. Additionally, we hoped to make some comparison between visual search and reading using the moving window paradigm.

With respect to the size of the perceptual span (or the area from which useful information can be obtained during a fixation), we found that the size of the span in the search task was very similar to the size of the perceptual span when subjects are reading rather than searching for a letter. In both situations, the span is asymmetric in the direction the eyes are moving extending 3-4 letters to the left of fixation to about 15-16 letter spaces to the right of fixation. When searching through arrays consisting of similar (or confusable) letters, subjects in the search task seemed to be able to use information from a more restricted area than when the arrays consisted of dissimilar (or non-confusable) letters.

With respect to the number of letters processed per fixation in the search task, the results suggested that up to 12-16 letters received some type of processing (as deduced from the search time data) while no more than 3-6 letters were identified (as deduced from saccade size data). In fact, the number of letters identified seemed to be contingent upon the background characteristics; more letters were identified (up to 6) when the distractors were dissimilar to the target than when the distractors were similar (roughly 3-4 letters identified). That up to 12-16 letters received some type of processing is evident from the fact that when we computed search time as a function of the number of letters that were available in the array, asymptotic levels of performance were reached when 12-16 letters were available. The exact number of letters that received some type of processing was also contingent upon background characteristics; when the distractors were dissimilar to the target letter, processing over a greater range of letters (16) occurred than when the distractors were similar (12 letters) to the target. However, it is clear that no more than 6 letters were identified per fixation; search performance in Experiment 2 did not differ when string size was 6 or 8 for any window size. That is, search time was identical when string size was 6 with a 1S window to string size of 8 with a 1S window and this lack of difference was consistent for all window sizes employed. Thus, we think it is safe to conclude that no more than 6 letters were identified per fixation. If we assume that saccade length reflects the number of letters that are identified per fixation, so that the eyes move to the next unidentified letter, then an estimate of 3-6 letters identified per fixation emerges. Further, it is clear from the experiments that saccade length is greater when the target is embedded in dissimilar letters than when it is in similar letters, implying that more letters are identified per fixation when the distractor letters are dissimilar to the target. The fact that the eyes move considerably less than the size of the perceptual span has also been noted in search tasks (Jacobs, 1986) and in many reading experiments (Ikeda & Saida, 1978).

What exactly does it mean to say that up to 16 letters "received some type of processing?" Our sense is that the letters closest to fixation (3 or 4 left and right of fixation) are identified while letters further to the right of fixation (out to about 12-16 letter spaces from fixation) are processed only at the level of gross featural information. This gross featural information may be used to alert the processing system to possible targets that are in the parafovea. In other studies, we have found that when dissimilar letters were inside the window, but similar letters were outside the window, search was slowed presumably because the gross featural information obtained parafoveally alerted the system that potential targets were upcoming. Since these similar letters were present on each and every fixation, search was slowed in comparison to a condition in which dissimilar letters were both inside and outside the window.

To provide a direct comparison between search and reading, in Table 2 we have computed the search times from Experiment 2 for the 1S and 2S windows (collapsed across other variables) and the processing time per character from a study (Experiment 2 of Rayner et al, 1982) in which conditions were almost identical to our search conditions, except that the subjects were reading. In both sets of conditions (search and reading) the window to the left of fixation extended to the beginning of the currently fixated string (or word) and outside of the window area other letters were replaced with Xs. The major difference between the two situations (other than the task) is that in the reading task, each string (word) was of variable length while in the search task each string was of constant length for a given trial. Hopefully, by collapsing across the different string lengths we have equalized that factor somewhat as the mean string length when the data are collapsed in such a manner is 5 letters per string, which is roughly equivalent to the average word length of the sentences used in the reading situation. Examination of Table 2 reveals that processing rates in Experiment 2 with dissimilar letters were very similar to the reading situation.

Table 2

Processing time per character (in milliseconds) in search and reading conditions with a 1S and 2S window.

	1S	2S
Search (Similar Letters) Experiment 2	107	87
Search (Dissimilar Letters) Experiment 2	58	46
Reading (Rayner et al, Experiment 2)	73	49

Despite some similarities between search and reading, it should be pointed out that they are very different tasks. Searching for the presence of a single letter is much different than reading for comprehension. While in reading there is some variability in how much can be processed per fixation as a function of contextual constraint (Balota, Pollatsek, & Rayner, 1985), the variability is not as great as that due to the characteristics of the distractor items in search. It is often assumed that search is faster than reading, but the validity of that assumption again depends on the characteristics of the distractor items; when the target is embedded in letters that are very similar to the target, search is actually quite a bit slower than reading. The rate at which subjects searched for the target letter in our studies was quite similar to that obtained in other studies (Neisser, 1964; Brand, 1971) so that the fact that our subjects searched horizontally while others have typically searched vertically is irrelevant. When the search time in these other studies was converted to milliseconds per character, the rates ranged between 40-100 ms per character (as in our experiments), depending upon the exact nature of the condition.

Perhaps the greatest similarity between reading and visual search (when subjects are free to move their eyes) is that both tasks are highly constrained by acuity factors and by the motor control programs involved in initiating the next saccade. Lack of visual resolution of the letters in parafoveal vision due to acuity limitations necessitates that subjects move their eyes frequently. However, it is clear that the motor programs involved in actually moving the eyes are quite time consuming with the minimal oculomotor latency being around 175 ms (Rayner, Slowiaczek, Clifton, & Bertera, 1983). From experiments (Rayner, et al., 1981) in which a visual mask was presented on each fixation and from rapid serial visual presentation (RSVP) experiments (Potter, Kroll, & Harris, 1980) it is clear that encoding processes in reading can be completed in about 50-60 ms. Likewise, multiframe experiments in visual search make it clear that 4-6 letters can be processed in 50 ms (Fisher, 1982). Thus, acuity factors and the reaction time of the eyes both place severe limitations on the rate of processing during search and reading.

In summary, we believe that the moving window technique offers a viable paradigm for studying visual search processes under relatively natural situations in which subjects can move their eyes, but in which the number of letters that are available for processing can be precisely controlled. Varying the relationship between characters inside and outside of the window area also appears to be very promising for investigating critical properties of the search task. Future research using this paradigm should yield valuable insights into visual search processes.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

EYE MOVEMENT PATTERNS IN A VISUAL MATCHING TASK AS INDICATORS FOR MULTIPLE CODING[1]

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This experiment in analogy to Santa (1977) contrasted subjects' memory for verbal and figural displays. The experimental paradigm involved a same/different reaction time task in which 27 subjects were shown displays containing either simple geometric figures or their typed equivalents. Subjects' eye movements were measured during their working of the entire task. The factors "kind of material" and "spatial arrangement" affected both the storing of material in memory and retrieval and comparison processes. Evidence found in support of differing codes is discussed in the context of a multiple coding model.

INTRODUCTION

The newer approaches to the understanding of knowledge representation in human memory are based on a multiple coding model. Anderson (1983), for example, proposes a tri-code theory which distinguishes the following three codes: an abstract proposition which encodes meaning as distinguished from a temporal string which encodes the order of a set of items; and a spatial image which encodes spatial configuration. A comparable differentiation is to be found in the earlier work of Wallach and Averbach (1955). This multiple coding model neutralizes the polarization of the so-called imagery debate in which Anderson and Bower (1973), Pylyshyn (1973), and Anderson (1976), to name the principle adherents, advocated a uniform propositional form of representation exclusively. This position stood in marked contrast to Paivio's dual-code theory (e.g. 1971).

Evidence for the existence of an image representation as distinct from a string representation was documented by Santa (1977) in a series of experiments. He used a reaction time procedure to demonstrate that short-term verbal representations are ordered in a temporal sequence. The representation of geometric figures, on the other hand, reflects the spatial relations between the stimulus elements.

The subjects' task was to decide as quickly as possible whether two stimuli presented one after the other (original and comparison stimuli) were the same or different. Each stimulus display consisted of three elements, either simple geometric figures (figural material) or names for them (verbal material).

Santa's arguments for a multiple coding model are based on the following experimental results: When the original elements were ordered in a two dimensional triangular arrangement, the reaction times were shortest for figural material when the comparison material was identically arranged. In contrast, the reaction times for verbal material which was arranged in the original in a triangle were shortest when the comparison material was arranged linearly in a horizontal row. Santa concludes from these results that verbal material is most probably stored in a temporally ordered sequence. The representation of figural material, in contrast, retains characteristics of the spatial relations.

In an attempt to describe in greater detail the cognitive requirements presented by Santa's experiments, we propose to differentiate the following processing phases: (1) encoding and storing the original material; (2) rehearsal of the material in the interval between learning and reproduction; (3) encoding the comparison material; (4) retrieval and comparison processes; (5) decision. - The reaction time which Santa measured and evaluated was the time required for phases 3 through 5. The question of whether or not the different forms of coding influence the processing phases (1) and (2) remains open.

Our goals in this explorative study were threefold: (a) The experimental procedure should allow for the inclusion of the cognitive processes for the entire length of the task, especially the first phase of encoding and storing the original material. (b) On-line data should be available and directly related to the processes as they occur. (c) To allow comparions with Santa, important components of his experimental design should be taken into consideration.

To reach these goals we used the measurement of eye movements as a substitute for reaction times. These measurement values made it possible to gather data about processing phases (1) as well as (3) through (5). We were, therefore, able to examine the influence of different types of codes in the phase of storing the relevant material in memory as well as in the retrieval and comparison phase.

METHOD

Subjects: 27 male and female students from various faculties. Each subject was tested alone in a session lasting 45 minutes.

Stimuli: The stimulus material consisted or 96 slides. Half of these slides served as test material (original slides), the other half as comparison material. Each slide contained three elements taken from two groups of material: words or figures. The figure were: triangle, ellipse, circle, arrow, square, and rhombus. The words were the names for these six figures.

Each slide contained either words of figures exclusively. The elements were ordered in two ways: (1) string arrangement, with all elements ordered in a horizontal row, (b) triangular arrangement, with three elements ordered in the form of an equilateral triangle, with two elements on top and one below. - Each stimulus pair consisted of an original and a comparison slide with the two slides in a pair always having the same arrangement, either triangular or string. - Half of the comparison slides contained dissimilar elements, half of the comparison slides contained the same elements as the original slides. The stimulus pairs containing the same elements were further subdivided into an identical group in which the elements were not only the same but were also arranged in the same position, and a transformed group in which two elements were transposed. - From the position of the subject relative to the projection screen there was a visual angle of approximately 2 degrees for the width of the elements and 11 degrees for the distance from the midpoint of one element to the midpoint of the next.

Procedure and apparatus: The stimulus material was presented on a two-switch projector and the length of projection was controlled by a programmable computer attachment to the projector. - Before the projection of the original stimulus material, a fixation point was projected for three seconds. Then the original slide was presented also for three seconds, followed again by a fixation point (three seconds). The comparison slide was then presented and the subject was to decide whether the material on the comparison slide was the same or different from the original. He or she communicated this decision by pressing one of two buttons, one labeled "same" and one labeled "different" and the reaction time was recorded.

Eye movement measurement: The eye movements were measured by tracking the corneal reflection center with respect to the pupil center via a video camera. The x and y coordinates were calculated every 20 milliseconds. The coordinates were recorded and monitored by computer (system DEBIC 84).

As the unit of analysis we used one gaze, defined as an uninterrupted sequence of fixations on the same element position, defined as a circle of 2.9 degrees around the midpoint of the element, with a minimum duration of 80 msec. Such "global" measures of fixations are assumed to reflect higher level cognitive processes (cf. Just and Carpenter 1976; Kliegl, Olson and Davidson 1983).

RESULTS

1. A comparison of the storing and retrieval phases

The storing phase was defined as the projection time of the original slide (3 sec). The retrieval and comparison phase was the projection time of the comparison slide. As may be recalled, this time period was determined by the subject and defined as his or her reaction time.

Our first comparison concerns the difference between storing and retrieval phases for the four stimulus categories. The dependent variables were gaze frequency and gaze duration. Gaze frequency was defined as the total number of gazes per slide, summed over the three positions. Correspondingly gaze duration was the length of time per slide in which a subject viewed all three positions. Per subject the relative percentage of gaze frequencies and gaze durations for each stimulus category was then determined. These relative percentage values were used as the raw data for all of the following computations.

Table 1 includes the averaged percentages of gaze durations for each stimulus category during the two phases. Significant differences via t-Test could only be demonstrated for gaze durations namely in the categories words-triangular and figures-triangular. (The region of rejection throughout this article is $p < .05$.)

Table 1
Averaged percentages of gaze durations for the four stimulus categories

stimulus category	processing phase	
	storing phase	retrieval phase
words - string	26.1	27.4
words - triangular	23.3	25.0
figures - string	26.5	25.7
figures - triangular	24.1	21.9

2. Storing phase

The next analysis refers to gaze frequencies and durations in the storing phase. The effects of the different types of material (words vs. figures) and of the variations in arrangement (string vs. triangular) on the dependent variables (gaze frequency, gaze duration) were examined, via two-factor analyses of variance. (All effects described in the following text refer to statistically significant main effects or interactions.)

Figure 1 shows that figural material is stored with fewer gazes than verbal material. Independent of this, a triangular arrangement requires fewer gazes than does a string arrangement. For gaze durations only the arrangement effect could be seen. Storing the triangularly arranged material required less gaze time than did a string arrangement.

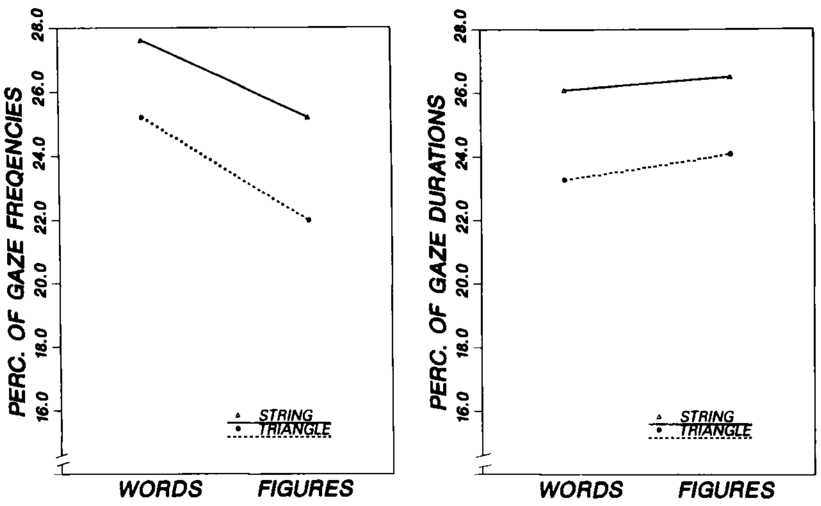

Figure 1
Percentages of gaze frequencies and gaze durations (means) - original slides

3. Retrieval and comparison phase

3.1 Material and arrangement effects

As in the storing phase we first examined the effects of the different types of material and arrangement using two-factor analyses of variance.

As can be seen in figure 2, figural material and triangular arrangement again required fewer gazes. In addition, the interaction between the two factors indicates that the arrangement effect was more pronounced for figural material than for verbal material. The gaze durations were only affected by the arrangement just as in the storing phase.

3.2 Effects of the transformation of elements

The following analysis concerns "same" answers exclusively. The answer "same" was to be given (a) when the original and comparison slides were identical and (b) when the elements were identical but in a transformed order. The effects of these transformations on retrieval and comparison processes were analyzed by three-factor analyses of variance with the factors: material, arrangement, and order of the elements (identical vs. transformed).

Figure 3 shows that in the retrieval and comparison phase the stimulus elements were scanned less often and for shorter lengths of time when arranged triangularly than when arranged in a string. The results also indicate that a transformation of elements led to more intensive scanning.

3.3 Effects of the answer alternatives "same/different"

In this section we examine the effects of the factor answer alternatives on the information processing in the retrieval and comparison phase. Therefore, the

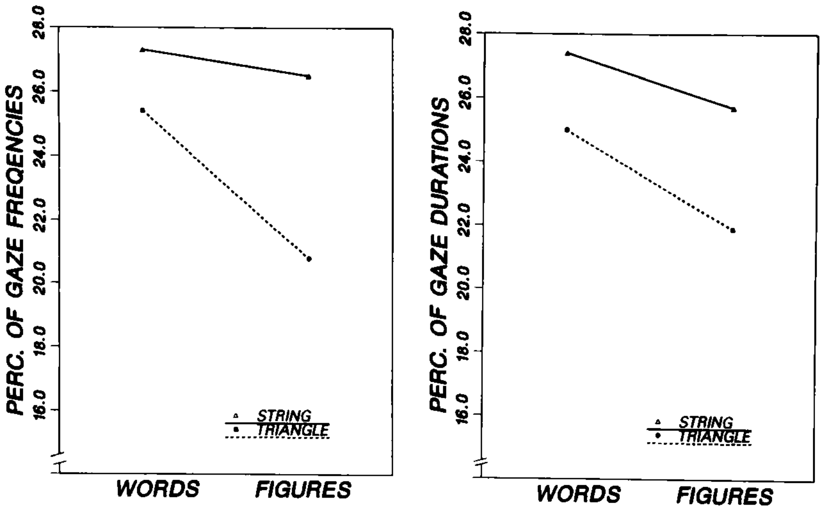

Figure 2
Percentages of gaze frequencies and gaze durations (means) - comparison slides

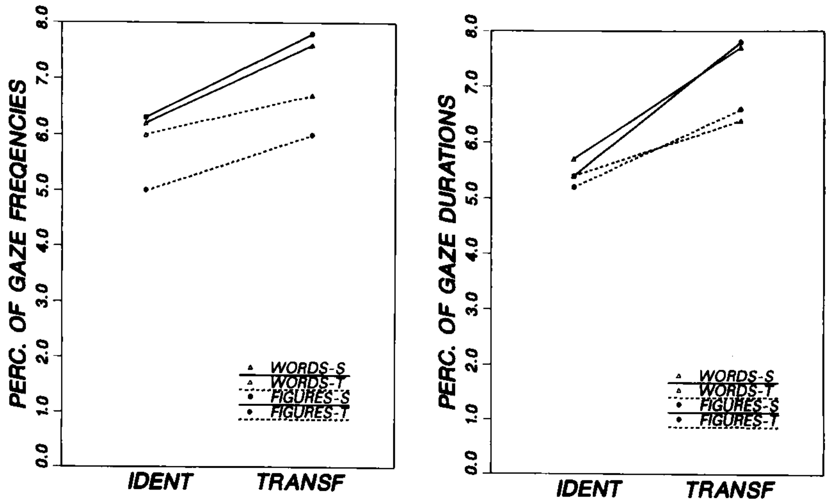

Figure 3
Percentages of gaze frequencies and gaze durations (means) - "same" comparison slides

following analyses concern the data for both possible answer alternatives (same/different) (three-factor analyses of variance with the factors: material, arrangement, and answer alternatives (same vs. different)).

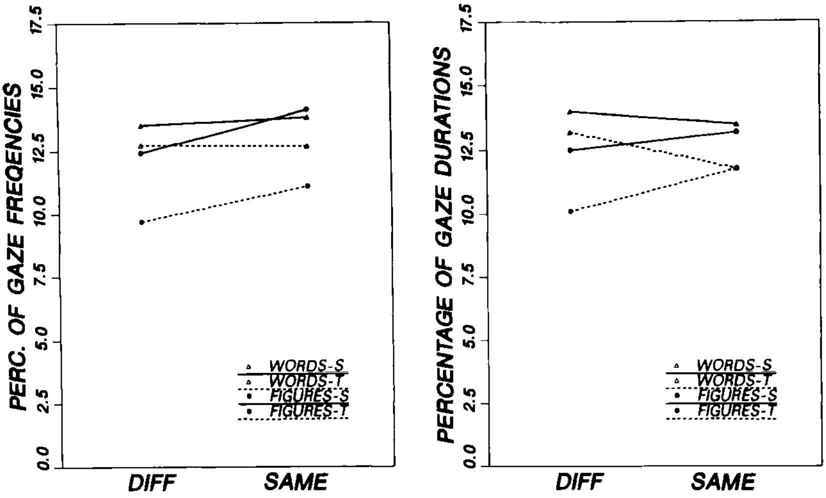

Figure 4
Percentages of gaze frequencies and gaze durations (means) - "same" vs. "different" comparison slides

One can see in figure 4 that in the retrieval and comparison phase fewer gazes had to be used for figural material and for the triangular arrangement. - The interaction of these two factors, material x arrangement, reflects the fact that the arrangement effect is more pronounced for figural material than for verbal. The main effect in the case of the answer alternatives indicates that "different" answers require fewer gazes than "same" answers. The material x answer-alternative interaction indicates that this difference is more pronounced for figural than for verbal material.

For gaze durations a string arrangement again led to longer gazes and therefore to a more intensive visual processing than did a triangular arrangement. The material x answer-alternative interaction indicates that "different" answers require shorter gaze times than "same" answers only in the case of figural material.

3.4 Gaze sequences

Each slide consisted of three elements and could be scanned completely with three gazes. Sequential scanning, which would reflect a string representation, should have the scanning order: position 1-2-3. We, therefore, computed the percentage of 1-2-3 gaze alterations to the entire number of gazes in the retrieval and comparison phase for all four stimulus categories separate for the two answer alternatives. The results are given in table 2.

Table 2
Percentage of 1-2-3 alterations in the retrieval phase

stimulus category	answer category same	 different
words-string	51.16	53.52
words-triangular	51.02	46.93
figures-string	41.73	31.94
figures-triangular	33.47	30.67

DISCUSSION

Santa (1977) suggested on the basis of his experiment a multiple coding model for the representation of information in memory. According to this model figural material which is presented in a triangular arrangement is represented as an image and associated with holistic or parallel processing. Verbal material, even when offered in a triangular arrangement, leads to representation in string form, that is in a temporally sequential order. Santa's experiments, however, leave open the question of whether or not these different forms of coding in memory already play a role in the first phase of the storing of information in memory or first become relevant in retrieval and comparison processes. Our experiment was designed to examine this question.

The following interpretation of the data is based on the assumption that the independent variables which we examined (material, arrangement, answer alternatives) do not correlate with the finding of the correct or incorrect answer. The fact that close to 100% of our subjects' answers were correct eliminates the possibility of this systematic effect.

Our first question was whether or not variations in the stimulus material (words vs. figures) as well as in the arrangement of the stimulus elements (string vs. triangular) would influence storing processes and retrieval and comparison processes in the same way. We refer here to the results of four analyses of variance with the two factors material and arrangement using gaze frequencies and gaze durations as dependent variables (see figures 1 and 2). The material as well as the arrangement variation affected both processing phases in the same manner: string arrangement and words required more intensive visual scanning than did triangular arrangements and figural material. If one assumes that figural material and triangular arrangements favors holistic processing, then it can be said that holistic storing and retrieval processes take place more quickly than sequential processing.

Differences between the two processing phases occured, however, on an additional level. When the distributions of the relative amounts of time required across the stimulus categories for each of the two processing phases are compared (see table 1), one arrives at the following conclusions: The sum of time for gazes directed at figural material was relatively greater in the storing phase than in the retrieval and comparison phase. In contrast, the storing phase for verbal material required a relatively lesser amount of time. Independent of the fact that figural material demanded in both phases less scanning (gaze frequencies), the time required for the storing of this material was more than required for its retrieval and comparison. It is possible that storing processes for figural material require additional capacity which is then no longer needed for retrieval. The opposite applies to verbal material. It can be stored with less effort but is then retrieved with relatively more difficulty. Do these results mean that the characteristic processing of figural material requires more elaborate storing in comparison to later processing steps? If yes, a contrasting distribution would have to be assumed for verbal material.

As the effects of the answer category "same/different" as well as the variation in the position of the elements (identical/transformed) could only be observed in the case of the comparison slides and are, therefore, only relevant for the retrieval phase, we close our analysis of the differences between the storing and retrieval phases and turn our attention to the retrieval/comparison phase.

We first examine the transformation effect for "same" answers. The arrangement factor produced the effect already known, that string arrangements require more intensive visual scanning than do triangular arrangements. In addition the transformation of the elements on the comparison slides also led to more intensive scanning (see figure 3).

In agreement with Santa's results it can be said that retrieval and comparison processes can be carried out most economically when the elements of the original and comparison material are arranged in the same positions. In contrast to Santa's experiments, the main effect which we found for arrangement contradicts the idea that a string arrangement in the case of verbal material can be processed with less effort than a triangular arrangement. We found no evidence of a string code for verbal material which was arranged triangularly.

The next evaluation includes the difference between the answer alternatives "same/different" (see figure 4). As in all the analyses mentioned so far, an arrangement effect was found. Also, in this evaluation, which makes use of all the data (including both answer categories), there was a significant material effect. In addition, the inclusion of the factor answer alternative resulted in two interactions for the factor material: one with the factor arrangement and one with the answer alternative factor. At this level of observation a new result was that the answer "different" was associated with less intensive scanning than the answer "same". This effect was especially pronounced for figural material. It was also true of the arrangement factor that the effect was more marked for figural material.

Retrieval and comparison processes require less cognitive effort when there are different elements on the comparison slide. These results can be interpreted as evidence for a non-exhaustive memory search in the case of different elements.

The interaction between the factors answer alternative x material can be interpreted as follows: The holistic comparison process characteristic for figural material is stopped by a "different" answer sooner than is the case for the sequential comparison processes associated with verbal material.

In our analysis of gaze sequences we have found indications for the existence of string representations in memory. If these string representations do exist, then a strict, sequentially ordered scanning process, namely from left to right and from top to bottom, must be observed in the retrieval and comparison phase. In the three-step alterations (1-2-3) which we counted, such scanning behavior should be relatively more frequent for words than for figures. Indeed the values found do reflect this relationship (see table 2). We therefore assume that the code for words is more nearly in accordance with a string code than the code for figures.

In summary the following can be concluded: The type of material (words vs. figures) as well as the arrangement (string vs. triangular) influences the way in which the material is stored in memory. The relevance of these two factors on retrieval and comparison processes can also be seen. We found evidence for different types of coding as well: evidence which we regard as support for a multiple coding model. However, in our opinion, the relation of stimulus characteristics to specific memory codes cannot be accepted as exclusively as indicated in Santa's results. Apparently there are modifying conditions for stimulus characteristics which can influence the memory code.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

READING A MESSAGE WHEN THE SAME MESSAGE IS AVAILABLE AUDITORILY IN ANOTHER LANGUAGE : THE CASE OF SUBTITLING

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In Experiment 1, subjects reported on the speed of three presentation times of subtitles (4-, 6- and 8-seconds rules), with the 6-seconds rule as the one used by most TV stations (normal presentation time). In Experiment 2, three time rules (2-, 4- and 6-seconds rule) were used in three different tapes of the same movie and the eye movements were recorded. Subjects did or did not master the spoken language; a third group did not receive the sound track. The findings suggest that, under normal presentation time, time spent in reading the subtitle does not change as a function of the knowledge and the availability of the spoken language, due to the longstanding experiences of our subjects with such a presentation time. A number of episodic effects of the movie are to be explained by their confounding with the number of lines in the subtitle : As the time to switch from the movie to the subtitle is more or less the same in all cases, more viewing time is available with two lines. In general, processing of subtitles seems to be an automatic or "encapsulated" activity, at least if it is not disturbed by abnormal presentation times.

INTRODUCTION

In d'Ydewalle, Muylle and Van Rensbergen (1985), we showed that TV watching behavior provides a rich source of information about how the subjects divide their attention in a perceptual situation containing at the same time visual stimuli and auditive information. Moreover, both sources of information are partially redundant, as the content of verbal discussions between actors in the movie can often be predicted by the episodic sequence within the movie. Watching behavior of adults is clearly largely effortless. One may say that both, divided attention between the two, are largely automatized with adults. Disentangling the mechanisms of attention in such a situation is not easy, mainly due to the lack of appropriate dependent variables. There is a particular situation in smaller language communities where foreign movies are not dubbed (i.e. the spoken voices are replaced by voices in the local country language) but are provided with subtitles. Here, a third source of information is made available. The text lines are again partially redundant with the audio channel (particularly if one knows the foreign language) and with the visual image. Our research programme focuses on the reading behavior in the subtitle. The time in the subtitle, as a function of the information available in the audio channel and the visual image, gives us the dependent variable which should allow us to study the various attentional processes in TV watching behavior.

In many countries, roughly the same rules of thumb are used for timing the subtitles. Two lines together, each with a maximum of 32 characters and spaces, can be used one at a time. If there are two lines x 32 characters and spaces on one subtitle, it is displayed for six seconds. Shorter subtitles are time-scheduled proportionally according to this rule (six-seconds rule). Nobody seems to know how the six-second rule was arrived at. Accordingly, d'Ydewalle, Muylle and Van

Rensbergen (1985) applied three different time-rules : Four-, six- and eight-seconds rules were randomly mixed throughout the 104 subtitles within a German movie series (about 10 minutes play-time). The proportion of time spent in the subtitled area as a function of the presentation time decreased linearly as a function of the four- (28 %), six- (23 %) and eight-second (21 %) rules. One also stayed longer on a two-line of text (28 %) than on a one-line (20 %).

The analyses on the time in the subtitle failed to reveal any typical reading behavior in the subtitle : During the presentation of a subtitle, there was considerable back and forth jumping between the visual image and the subtitled area. The absence of reading behavior could be attributed to mixing the several time rules within the same video presentation. As fourty per cent of the Belgian Flemish TV programmes are subtitled, our subjects were well acquainted with the six-seconds rule presentations but were now facing some subtitles with either shorter or longer presentations. Also, the time rules were randomly mixed throughout the movie. Accordingly, subjects could not adapt themselves to the different time presentations.

EXPERIMENT 1

The above reasoning assumes that the subjects are able to discriminate the subtitles according to their time rules. Therefore, Experiment 1 uses the same movie with the same presentation time of the subtitles as in d'Ydewalle, Muylle and Van Rensbergen (1985). For each subtitle, subjects had to report immediately whether the presentation time was too fast, appropriate or too long. It should be clear that this on-line reporting focuses the conscious attention of the subjects to the presentation time. In d'Ydewalle, Muylle and Van Rensbergen (1985), subjects were naïve with respect to the presentation time of the subtitles : They did not know that our research interest concerned the subtitling, and no one complained overtly about the presentation times. Two main effects were obtained : The faster the presentation time of the subtitles, the more the subjects complained about their speed, and one line is experienced as faster than two lines. We also wanted to know in which combination of our 2 (lines) x 3 (time rule) design of subtitles, subjects have no complaints about the speed of presentation. The only combination where subjects report an appropriate timing is two-lines/six-seconds rule.

At least two conclusions may be drawn from this on-line reporting experiment. Subjects are clearly able to discriminate consciously the subtitles according to the time rule. Secondly, one-line presentation, whatever the time rule, is experienced as quicker (and too quick with the four- and six-seconds rule) than a two-lines presentation. d'Ydewalle, Muylle and Van Rensbergen (1985) found proportionally more viewing time in the subtitle with a two-lines presentation than with a one-line presentation. Our initial interpretation was that processing two lines is intrinsically more demanding than one line : Experiment 1 clearly rejects this interpretation, as more time complaints are found with a one-line presentation. Our suspicion is directed to the time latency to jump from the visual image to the subtitle when a new subtitle is presented. Assuming that this latency is independent from a one-/two-lines presentation, obviously there remains proportionally less time available for processing the subtitle with one line.

EXPERIMENT 2

The major purpose of Experiment 2 was to investigate the time rule in independent samples of subjects. The absence of reading behavior in d'Ydewalle, Muylle and Van Rensbergen (1985) could have been due to mixing the time rules within the same movie, making adaptive reading rates next to impossible. Experiment 1 of the present report clearly reveals that subjects are able to discriminate within the movie the different time rules. Their ability to discriminate was revealed by their verbal reporting after having seen the subtitle : In our former study, subjects could not predict which time rule would be applied at one particular subtitle at its onset and their attention was not consciously directed to the time of presentation of the subtitles. In summary, spontaneous (automatized) processing and overlearned reading patterns of subtitles were made next to impossible in d'Ydewalle, Muylle and Van Rensbergen (1985). It is the primary purpose of Experiment 2 to look at watching behavior under normal presentation times, and to compare the data of this condition with a number of other conditions in order to unravel the different processes more clearly.

Experimental design, equipment and predictors

Three different tapes of the same German movie were prepared, applying a two-, four- and six-seconds rule. The eight-seconds rule was no longer used because there were some problems of overlapping subtitles when the conversation in the movie (the sound track) went too quickly : The onset of the subtitle presentation had always to correspond with the voice onset. By way of reminder, the six-seconds rule is the reference condition as used by most TV stations. With one line of presentation, sentences contained words using up to 32 characters; with two lines, subtitles were sentences using 33 to 64 characters.

In order to investigate the details of attentional processes, we added two series of conditions. As a kind of control condition, the sound track was switched off in one third of the conditions : With no audio channel, the subjects have to read the subtitles in order to understand the movie, provided that the visual image does not contain sufficient information about what is going on. Comparing the two series of conditions, with and without sound track (sound and no sound conditions), will help us to get an idea how the information of the sound track is used to follow the subtitles and to understand the movie. Until now, our subjects were assumed not to be able to follow a spoken conversation in the language of the foreign movie. Absolute ignorance of the spoken language, however, cannot be assumed. The vocabulary of the Dutch language of our subjects shares many words from the German language. In order to control the knowledge of the spoken language, we included a third group of subjects who were judged by the Department of Linguistics to know the German language as well as native German speakers (language condition). In all conditions, there were an equal number of male and female subjects. Accordingly, the experiment consisted of 18 separate samples of subjects : 3 conditions (sound, no sound and language) x 3 time rules (two-, four- and six-seconds rules) x 2 sexes. For each subtitle separately, we defined how much time the subject looked in the subtitled area.

The equipment (DEBIC 80), based on the pupil-center corneal-reflection method, provided a registration sampling rate of 50 Hertz (a sampling every 20 milliseconds). A head-tracking mirror system gave the subject considerable freedom to seat in a relaxed way in front of a regular TV screen (approximately 180 cm distance).

Three sets of predictors were entered. The first one covers (generally speaking) the characteristics of the words in the subtitle (word characteristics). It included the number of syllables, the number of words and the average logarithm of normative frequency of the words used in the subtitle (as compiled for Dutch words in Uit den Bogaart, 1975). We called the second set of predictors the surface structure of the subtitle and this contained two vectors, one vs. two lines and the presentation time of the subtitle. The third set covers the episodic characteristics of the subtitle. This third set is subdivided into three groups of predictors. One group, three scene vectors, takes into account whether the speaker is the same or a new one as the one in the preceding subtitle, whether or not the subtitle is embedded within an uninterrupted conversation, and whether or not the subtitle starts a new episode in the movie (there were seven episodes in the movie). Following Just and Carpenter (1980), we called the second group the case assignments. There were six different case assignments in the subtitles (5 vectors) : An answer, a question, a statement, and subtitles including at the same time an answer and a question, or a question and an answer, or a statement and a question. The third group of episodic characteristics defines the different speakers (7 vectors).

Results

Overall, more variance is explained in the sound and no sound conditions than in the language condition.

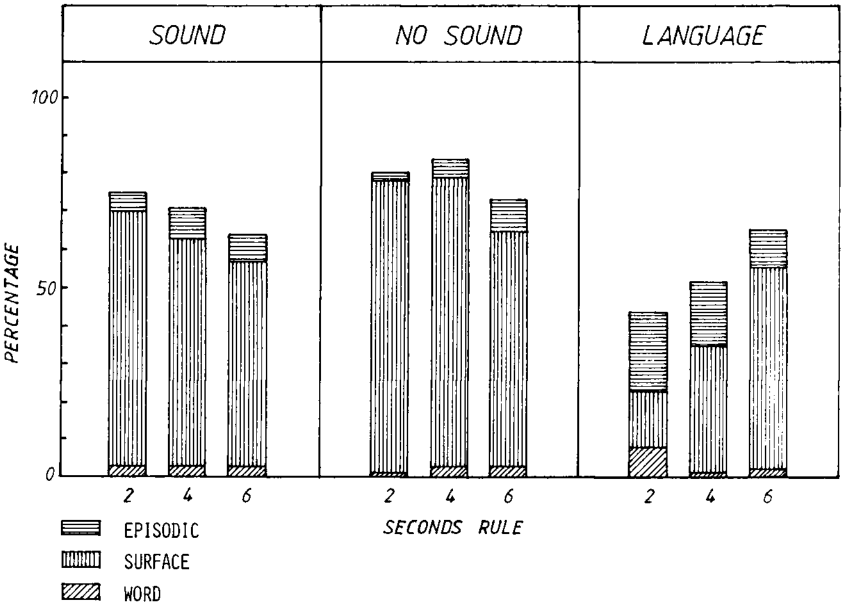

FIGURE 1. Proportion of variance explained by the surface structure, and the word and episodic characteristics of the subtitles, as a function of condition and time rule.

From Figure 1, it is also clear that variances due to the surface characteristics of the subtitle vary considerably as a function of conditions : 72 % in the no sound condition, 60 % in the sound condition and 34 % in the language condition. The variance due to the episodic characteristics changes considerably as a function of the conditions : 16 % in the language condition, and 5 % and 7 % in the no sound and sound conditions respectively. The variance explained by the word characteristics does not change with the conditions, and remains very small (overall = 3 %). In summary, the subtitle surface characteristics is the major predictor, and this is especially true in the no sound condition. Obviously, subjects' reading of the subtitle is much more influenced by the individual rate of presentation of the subtitle, as they badly need the subtitle to understand the story. It is apparent that in the language condition, the subtitle surface characteristics are less important and the episodic characteristics more important than in the two other conditions. Looking at Figure 1, the above description of the data is particularly clear with the two- and four-seconds rules while the general picture of the data with the six-seconds rule in the language condition almost matches the pattern of findings in all other conditions.

The episodic characteristics were divided into three subgroups : Scene vectors, case assignments, and the different speakers (people). The scene vectors and the people do not explain significantly more, or less variance as a function of the independent variables. Case assignments, however, vary considerably : With the two- and four-seconds rules, more variance is explained by case assignments in the language condition than in all other conditions. This set of findings is consistent with the general analyses with the three sets of predictors, ascribing the larger effect of episodic characteristics in the language condition to the larger impact of case assignments in the two- and four-seconds rules in the language condition.

Summarizing our analyses of the explained proportion of variances, a few conclusions can be reached. First, the set of subtitle surface characteristics is the major variable in explaining the variance in the no-sound condition. The largest proportion of unexplained variance is to be found in the language condition. Episodic characteristics have some importance, particularly the case assignments in the two- and four-seconds rules of the language condition. The word characteristics are of no importance at all in all conditions.

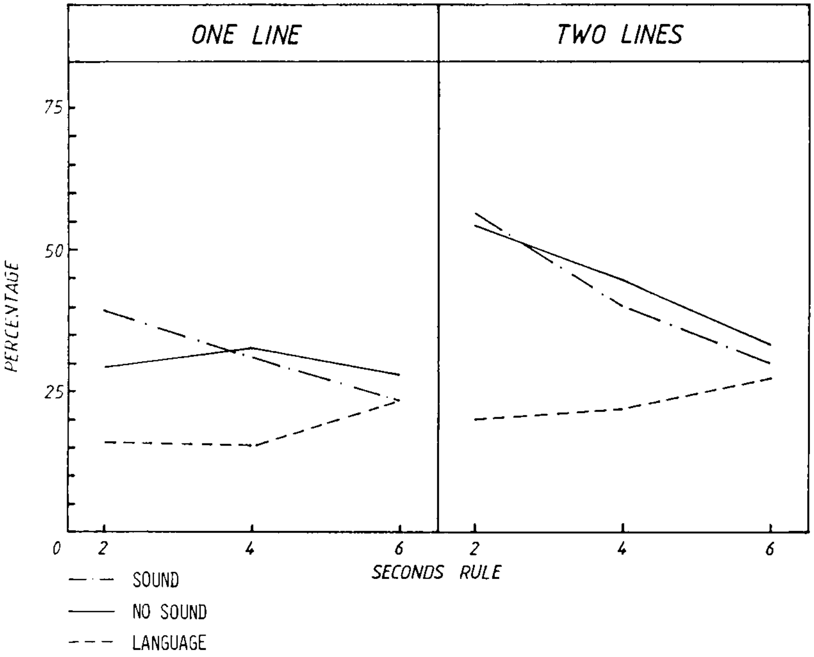

FIGURE 2. Percentage of time spent in the subtitle as a function of condition, time rule and one- vs. two-line presentation.

The next analysis is of the proportion of time spent in the subtitle. This proportion is calculated as a function of the presentation time of the subtitle. In all possible comparisons, subjects spend proportionally more time in a two-line presentation than in a one-line presentation. The difference is, however, smaller in the language condition and absent with the six-seconds rule. An obvious explanation for the difference between one- and two-line presentation will be offered later in the context of the analysis of how much time the subjects need in order to jump from the visual image to the subtitle when a new subtitle is presented. From Figure 2, it is also apparent that the sound and no sound conditions do not differ. This was quite unexpected : With no sound, we at least predicted more time in the subtitle. With the six-seconds rule, there is no difference between the three conditions. This is again an unexpected finding : The six-seconds rule is the one used by most TV stations, and one would have predicted less time in the subtitle when the subjects know the spoken language. With a speeded presentation time (two- or four-seconds rules), there is a difference between the language condition and the two other conditions. The increase is larger with a two-line presentation than with a one-line presentation. One can almost say that the subjects in the language condition spend approximately an equal proportion of time in the subtitle, independently of the time rule.

The next analysis is of the absolute time the subjects spent in the subtitle. For each subject and for one- and two-lines separately, the intercept and slope of the viewing time as a function of the presentation time were calculated. While the intercepts did not differ between the different conditions, the slopes considerably changed as a function of our independent variables. In Figure 3, the regression lines were drawn as a function of conditions, the time rules and one- versus two-line presentation. For one-line presentation, the regression line starts and stops with the shortest and longest presentation time; the same was done for the two-line subtitles.

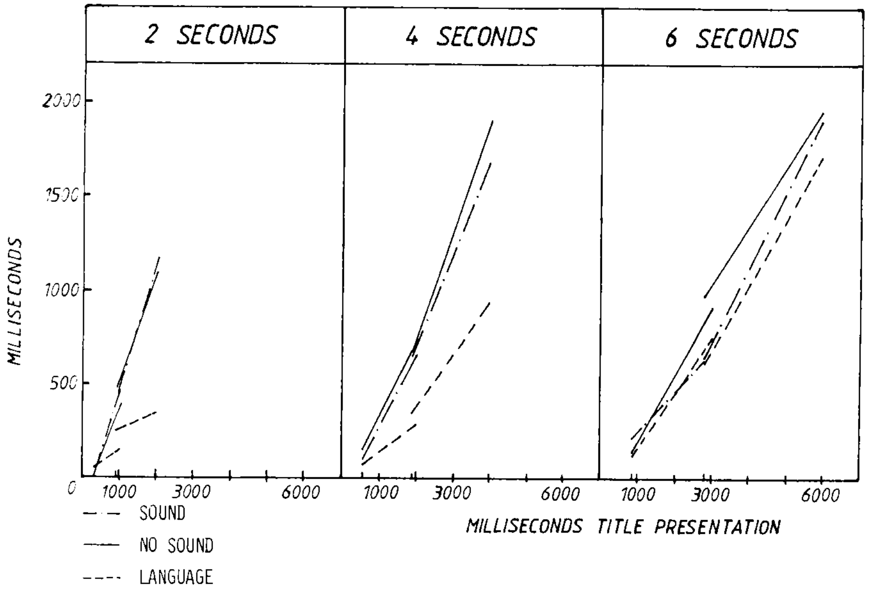

FIGURE 3. Regression lines of the time spent in the subtitle as a function of condition, time rule and one- vs. two-line presentation.

In the language conditions, all regression lines show approximately the same slope, independently of the time rules (average slope = 0.217). The regression lines in the sound and no sound conditions are remarkably similar but are heavily dependent on the time rule. With the six-seconds rule, they both show a slope approaching the one of the language conditions (0.307 and 0.330) : The slope of the sound and no-sound conditions becomes larger with the four-seconds rule (0.438 and 0.479) and even more with the two-seconds rule (0.685 and 0.584). There are almost no differences between the three conditions with the six-seconds rule. The difference between the language condition on the one hand and the two other conditions (sound and no sound) on the other hand becomes larger with a faster time rule (four- and two-seconds rules) : As the word and scene characteristics do not explain much variance and the explained variance does not vary with conditions, no further analyses were carried out on the average time spent in the subtitle as a function of our independent variables. In Table 1 is given the average proportion of viewing time as a function of the different case assignments; also given are the number of subtitles with one- or two-line presentations.

Table 1

Case Assignments	Proportion of Time	Number of Lines in Subtitle One Line	Two Lines
ANSWER	0.31	4	9
QUESTION	0.25	20	2
STATEMENT	0.33	22	31
ANSWER-QUESTION	0.26	1	0
QUESTION-ANSWER	0.38	1	2
STATEMENT-QUESTION	0.38	1	1

From Table 1 it is immediately clear that the number of subtitles with the three last categories of case assignments is too small to give meaning to the corresponding proportion of viewing time. Within the first three categories, the smaller proportion of viewing time with "question" is striking. However, it should be noted that subjects spent proportionally less time in the subtitle with one-line presentation than with two-lines presentation, and there were many more one-line subtitles with the "question" assignment. In a movie, a question is often framed in a rather short sentence. Accordingly, we consider this smaller proportion of viewing time to be due to the one-line presentation.

Breaking Table 1 down into three tables as a function of the three conditions (language, no sound and sound) shows that the smaller proportion of viewing time with "questions" is quite clear in the sound and no sound conditions, but completely absent in the language condition. It should be remembered that the difference between one- and two-line presentation almost disappears in the language conditions (see above), which indirectly confirms that the smaller proportion time with "questions" is due to the one-line presentation.

Speakers produce also major differences in viewing time. As in Table 1, the pattern of findings on the viewing proportions matches completely with the number of subtitles with one- and two-line presentation. If a speaker generally uses two lines of subtitle, the viewing time is proportionally larger. The matching between the proportion of viewing time and the one-/two-line presentation is everywhere present, except in the language condition with the six-seconds rule. It is precisely in the language conditions and with the six-seconds rule that the difference in the one- and two-line presentation becomes much smaller (see above).

Summarizing, it seems clear that the important effects of the case assignments and the different speakers must be explained by their confounding with the number of line presentations.

Why is the number of line presentations such an important variable ? One possibility is that the subjects need more or less a constant time in order to switch from the visual image to the subtitle at its presentation. If they need the same amount of time, less time is proportionally available for scanning the one-line subtitle. Table 2 gives the average latency (in milliseconds) from the visual image to the subtitle area as a function of conditions and the number of lines in the subtitle.

Table 2

Conditions	One line	Two lines
Sound Condition	318	350
No Sound Condition	382	348
Language Condition	331	472

All averages involved in the sound and no sound conditions do not differ from each other significantly. The only significant differences are between the two averages in the language conditions and between the two-line presentation in the language condition and the two-line presentation in the two other conditions. If the subjects need approximately the same amount of time to switch their attention from the visual image to the subtitle with one and two lines (sound and no sound conditions), there remains obviously more time available for looking at the subtitle in the two-lines presentation. Therefore, we obtained proportionally more viewing time in the subtitle with the two-line presentation, and in Experiment 1, subjects reported more complaints about the speed of subtitles with a one-line presentation.

The difference between viewing time in the one- and two-line presentation was much smaller in the language condition, but we see from Table 2 that it is precisely this condition which also uses more time to move the eyes to the two-line subtitles (reducing considerably the more time available with two lines). In our analyses of the proportion of time in the subtitle, it was also apparent that the difference between one- and two-line presentations was much smaller with the six-seconds rule. This cannot be explained by the latency to move to the subtitle, as the main effect of the time rule is not significant and is not significantly involved in an interaction.

GENERAL CONCLUSION

Although more variance in viewing time was explained by the presentation time in the no sound condition, other differences between the sound and no sound conditions failed to emerge. It is striking that the subjects don't spend more time in the subtitle when the spoken language is not available. Moreover, the subjects who know very well the spoken language still read the subtitle as much as the other subjects, provided that a normal presentation time is used (i.e. the six-seconds rule). In light of these findings, we suggest that reading behavior is more or less automatically elicited when a subject faces a text with the same message auditorily available. It is worthwhile to emphasize that reading a written message is faster and more efficient than listening to the same message, as the text still stays on the screen while a spoken voice immediately vanishes. It also should be remembered that our subjects are quite used to following movies with subtitles (either on the TV screen or in the movie theatre).

In d'Ydewalle, Muylle and Van Rensbergen (1985), we did not find reading behavior. Experiment 2 here seems to indicate that our former failure was due to mixing the different time rules in the same movie. We have to revise our former conclusion : Subjects do indeed read the subtitles, although considerable back and forth switching between the visual image and the subtitle obscures to a certain extent the normal pattern of eye movements in reading.

Of critical importance to explain a number of additional findings (e.g. the impact of episodic characteristics) was the difference between viewing time with one and two lines of the subtitle. In Experiment 1, subjects reported more problems in reading a subtitle with one line than with two lines. Experiment 2 showed that the subjects spent proportionally more time in a two-line subtitle than in a one-line subtitle. We were able to explain the difference by analyzing the latency to move from the visual image to the subtitle at its presentation onset. One implication is that TV stations should present subtitles longer with one line than the time as derived from the six-seconds rule. For subtitles with two lines, the six-seconds rule appears to be excellent for our sample of subjects. In these cases, the existing "rule of thumb" (the six-seconds rule) of most TV stations is supported by our data.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

SCANNING HABITS AND VISUO-MOTOR LEARNING

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Subjects (Ss) were required to reproduce a complex sports skill. Horizontally aligned still rows were supplied for instruction. Only when the criterion movement was unknown, did the predominant scanning direction exhibited by Ss match common reading habits even when picture arrangement was contrary to them. Scanning direction proved to be an indicator of task comprehension. In a second study, vertically arranged picture-text combinations were used for instruction. Independent of modality, Ss followed a top-down scanning strategy, although considerable age differences were found. Data obtained reject the notion of "semantic discrepancy" in concordant pictures and texts being beneficial to learning only when both modalities are attended to in a special serial order.

INTRODUCTION

Visual aids are widely used in physical education and sports. They are applied during the initial stages of motor learning, where they assist development of the "appropriate set of relative motions"(Newell, 1985) belonging to a complex sports skill such as pole vaulting or high board diving. So they address relative limb location, body position, movement direction and serial order of single limb movements. Their presentation usually precedes movement initiation.

Most frequently used are still rows and picture-text-combinations. These not only cover almost any skill in the various sport disciplines, but they also show a great variety of ways in which the information-bearing components (e.g. the single pictures in a still row) might be arranged with respect to each other. In fact commercial production of such teaching aids does not seem to follow any rules in this regard, and no effort has been made to evaluate the effectiveness of the various presentational alternatives.

Yet in our opinion it should not be considered insignificant in which sequence the different components of such visual instructions are looked at since the serial order of information intake is known to affect the pattern of comprehension in various ways. Also gaze distribution of subjects should not be expected to be arbitrary but instead follow certain conventions. Hence inadequately designed teaching material may prove detrimental to correct comprehension and even prevent students from complete and thorough examination of all instructional components.

Now it is well known that socio-cultural conventions such as reading habits may induce certain cognitive strategies of information processing which find themselves mirrored in "habitual" scanning patterns. Thus by means of such strategies and their corresponding scanning patterns, subjects anticipate the formal structure of the instruction´s contents. Visual teaching aids therefore should match such strategies. On the other hand, it is reported that so called "informative" areas, or features of particular visual attractiveness like illustrations, colours or contrasts, draw upon visual attention. Such effects are likely to interfere with those preset scanning and processing strategies mentioned above. But little is known in detail about such interference.

Certainly previous studies on this matter from the field of psycholinguistics and cognitive psychology can furnish general hypotheses on the interaction of visual design in teaching aids with habitual strategies of scanning and processing as exhibited by students. But although there has been a considerable amount of research on text reading and on scanning pictures in recent years, the results of these studies unfortunately do not seem to suffice as a guide line for proper production of visual teaching aids. In general they lack specificity relative to the task demands of the motor domain (i.e. generation, improvement and execution of action plans) and therefore they may also lack validity.

Thus improving the design of visual teaching aids in sports calls for empirical research of its own. To this end two experiments have been conducted. Both studies primarily meet practical demands. Yet at the same time forthcoming results may lead to further specification of theories and hypotheses adopted from psycholinguistics and cognitive psychology.

In both studies eye movement recording[1] serves to indicate the existence of certain scanning strategies. Also it is taken as a means to clearly relate learning results to either identification or non-identification of distinct features in the instructional materials. In case such relations turn out to be valid, eye movement recording eventually could be employed exclusively as a criterion test and thus replace the often intricate recourse to movement execution itself.

EXPERIMENT I

Still rows taken from sports exercises usually display a horizontal alignment of their single elements when presented for the purpose of instruction. But no convention is followed as to the direction of horizontal alignment. So a great many, if not the majority of those picture sequences to be found on book sheets and other devices proceed from right to left. As the culturally predominant reading direction is known to bring about a horizontal asymmetry in text reading (Witt, 1977; Rayner, Well, & Pollatsek, 1980), we assume that even for the purpose of extracting spatial relations and time characteristics necessary for subsequent movement execution, still rows will be "read" in the same manner, i.e. from left to right. Opposing arrangements of picture sequences then should conflict with that reading habit. That is, we expect the sequence of scanning the single pictures in a still row to reflect an organizing principle followed by subjects in generating a cognitive frame for movement coordination. In our view this hypothesis is not selfevident: The "semantic interactions" brought about by the informative features of still rows signifying spatial and space-time characteristics of the movement, may be quite different from those evoked by the words and letters of concordant texts. Therefore it seems questionable to apply principles derived from the field of text processing to the case of information intake from serially assembled pictures without any further warrant. And insofar as production of still rows and their application in practical teaching are concerned, an exemplary demonstration of the interplay between subjects' acquaintance with the movement presented, its (horizontal) alignment, subjects' scanning behavior, and task comprehension seems indispensable, since there still is little readiness in the physical education domain to take such aspects into consideration.

METHOD AND PROCEDURE

To each of two groups of adult objects (N_1 = 30; N_2 = 27) two still rows were shown in immediate succession for 15 s each. The first picture row always represented a gymnastics movement which was unknown to all of the subjects. The second one exhibited a track movement (hurdling) with which all subjects were well acquainted. The still rows shown to the first group of subjects both were arranged from left to right (Fig. 1a) while the same materials presented to the second group were assembled from right to left (Fig. 1b). It should be noticed that the representation of the gymnastics movement may be "read" from either side (i.e. left to right or right to left as well) and accordingly can also be interpreted as a backwards movement. This kind of ambiguity was intended since it is quite a typical feature of such pictorial instructions, especially in gymnastics, trampolining, judo, fencing, karate, etc. Clearly, the same does not hold true for the track movement.

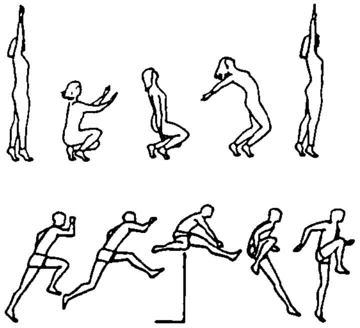

Fig. 1a: Materials presented to group I (assembled left-to-right)

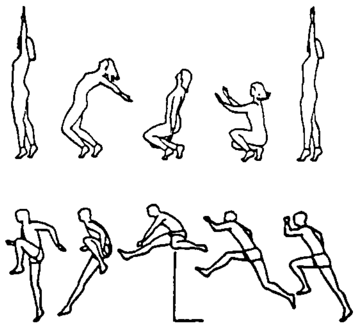

Fig. 1b: Materials presented to group II (assembled right-to-left)

Subjects were obliged to execute the gymnastics movement right after presentation (novel learning task), while with respect to the track movement they were asked to assemble single picture cards corresponding to previous presentation (recall of alignment). Since all subjects were familiar with hurdling, presentation of the track movement actually implies a recognition task.

Visual scanning was regarded as (horizontally) organized whenever a subject made at least three fixations in immediate succession that were all preceded by saccades with the same horizontal movement direction (i.e. either to the left or to the right), and that were distributed over at least three consecutive elements (single pictures) of a still row. Such fixation patterns are referred to as "directed gaze clusters". The more elements in a still row are covered by directed gaze clusters on average, the more consistent with a horizontal orientation the displayed scanning strategy appears to be in that case. Fixations not to be allotted to any gaze clusters were regarded as "unorganized". Thus gaze clusters may be characterized by their direction (left-to-right or right-to-left), by "amount of visual attention" (summed fixation duration, also referred to as "fixation time"), and by their "magnitude" (number of figurative elements covered).

On the basis of these three components a coefficient CS was calculated to characterize scanning behaviour of subjects and of treatment groups respectively.[2] Its value ranges from -1 to +1. This coefficient is positive as left-to-right gaze clusters are predominant; it is negative as right-to-left gaze clusters prevail. It approaches zero with an increase of "unorganized fixations", or when the amount of visual attention ("fixation time") accounted for by left-to-right gaze clusters equals that accounted for by right-to-left clusters.

Execution of the gymnastics skill by each subject was recorded on video tape for further analysis. In each case coordination was judged either "correct", "reversed", or "disordered", according to relative succession and movement direction of those elementary components of the complex motor task that actually were produced.

RESULTS AND DISCUSSION

Data presented in Table 1 reveal a distinct effect on scanning direction due to the sequence of pictures. The mean differences are significant for the learning task ($p<.05$) as well as for the recognition task ($p<.01$). At the same time there is an effect of scanning direction to be attributed to task demands, yet this is clearly restricted to such cases where subjects were confronted with still rows arranged from right to left ($p<.01$). It should be noted that under this condition the representation of the well acquainted track movement was scanned predominantly from right to left, according to its alignment, by about 70 % of all subjects of that group (cf. also negative sign of scanning coefficient in Table 1). Yet in contrast, under the same condition the representation of the unknown and to a certain extent ambiguous gymnastics movement still was scanned predominantly from left to right (which in this case was opposed to its intended alignment) by again 70 % of the same subjects (cf. also positive sign of scanning coefficient in Table 1).

Table 1.

Mean coefficients of scanning behaviour

sequence of pictures	task	mean CS	standard deviation	N*
left-to-right	learning	+ .63	.15	23
	recognition	+ .64	.23	23
right-to-left	learning	+ .35	.47	21
	recognition	- .32	.41	21

* Number of subjects with valid eye movement recordings

Thus subjects reveal a general expectancy as to still rows being assembled from left to right, although this becomes prevalent only when presentational materials are ambiguous. In other words, this "habitual" scanning behaviour is clearly overruled to a large extent when the "true" arrangement of a picture row is recognized, as can be inferred from comparison of coefficients presented in Table 1.

Does then interpretation of movement tasks coincide with predominant scanning direction? As can be inferred from Table 2, about 87 % of those subjects seeing a left-to-right representation of the gymnastics movement performed it in correct order, but out of those subjects confronted with a right-to-left arrangement not less than 70 % performed the movement backwards. This difference is highly significant ($p<.001$). Thus movement performance is well in concordance with the gaze sequences exhibited in viewing the gymnastics movement, which under both treatment conditions were predominantly oriented from left to right (cf. Table 1). This notion is supported by closer analysis of the learning results and gaze patterns produced by the single subjects: Of those subjects in the right-to-left condition, only a few performed the criterion movement in the "correct" serial order. But these very subjects attributed significantly more visual attention (i.e. summed fixation durations) on gaze clusters directed from right to left than the other participants ($p<.001$).

Altogether our data support the idea of some cognitive scheme which organizes both the strategy of scanning information-bearing sequences, and which may adjust strategies of information intake according to affordances of materials and task. At the same time the global scanning measures applied in our study prove to be a good indicator of the kind of cognitive concepts inferred from visual examination of still rows and similar instructional materials. Eye movement recording therefore may well be introduced for evaluation of such teaching devices. Moreover producers of teaching aids should give more consideration to the influence of common scanning habits.

Table 2.

Distribution of subjects in learning task with respect to preconceived categories of motor performance

sequence of pictures	motor execution of gymnastics movement			total number of subjects
	correct	reversed	disordered	
left-to-right	26	3	1	30
right-to-left	6	19	2	27

EXPERIMENT II

When initially acquiring the fundamental skills of a sports discipline (e.g. the butterfly stroke in swimming), beginners often are supplied with pictures along with corresponding texts for clear and detailed instruction. These materials usually are ready-made for self-instruction, and students individually may refer to them step by step as they proceed in learning that particular skill. Such materials are widespread in teaching at the primary and secondary school level, but they are also used in teaching adults.

Again there are numerous different ways in which pictures and text components are arranged on the various displays when exposed simultaneously.Possible consequences with respect to information intake and corresponding learning results have not yet been investigated. Present knowledge does not at the moment provide reasonable hypotheses for improvement of such teaching aids: Reasons for superiority of double encoding in motor learning are not clear yet; neither is it known under which conditions and to what extent double encoding is actually superior. As evidence on this issue is very scarce, we will rely on investigations of our own for further consideration:

In children, combining both a picture with a text ("combined" condition) has proven superior to the same information being presented by either picture or text only ("single" conditions). In adults, however, immediate acquisition scores did not at all differ from each other, while significant improvement of learning results occured only after a (filled) retention interval of at least 10 minutes for subjects under the "combined" encoding condition (picture and text). At the same time retention scores of adult subjects under both of the "single" encoding conditions (either picture or text) remained the same as compared with the respective immediate acquisition scores (Blischke 1985).

THEORETICAL CONSIDERATIONS

These findings contradict any premature generalizations: Obviously the motor reproduction of a visually presented criterion movement cannot be attributed merely to effects of the different encoding conditions. Also phenomena arising from perception and retrieval activities of the subject have to be considered. Thus the use of already existent and well-learned interpretive procedures ("strategic knowledge"; Shea, Hunt, & Zimny, 1985) may account for the somewhat surprising equivalence of immediate acquisition scores in adults. In that age group facilitation of retention then may have been due to the fact that only under the "combined" encoding condition the processing activities must be undertaken twice in all details (e.g. in each modality). So the individual learns more about the actual process of reconstruction and implementing the action plan at a given time than under the "single" encoding conditions (Lee & Magill, 1985).

Nevertheless, dual encoding in general is known to facilitate depth and spread of encoding (and thereby memory processes) as well (Klimesch, 1982), provided there is a "semantic discrepancy" with respect to those sets of meaningful items which can be derived from either the picture or the text component. Thus semantic discrepancy may be regarded as the actual cause for superior acquisition scores in children under the "combined" encoding condition, resulting in a more specific and elaborated representation of the movement to be put into action. And not being supplied yet with the strategic knowledge of adults, children at the same time can not make up for the handicaps of the "single" encoding conditions.

However, enrichment of information processing does not follow automatically from bimodal encoding conditions. There is some evidence for a "nominal" semantic discrepancy taking effect "functionally" only if picture and text are attended to in the proper serial order (Bock, 1983). In these studies the serial order has been found to induce either a more specific and elaborated (picture before text), or a more general and abstract level (text before picture) of cognitive analysis of the information presented.

POSING THE PROBLEM

At this point we may return to the problem of improving visual teaching aids. If there is an optimal sequence for looking at pictures and texts, this should be used as a means for improving information intake from visual teaching aids. To begin with, this supposition of course has to be scrutinized as to its validity in the domain of motor learning. And ways have to be found by which to influence the sequence in which subjects scan picture and text, when both are presented simultaneously.

Again we may fall back upon "habitual" scanning strategies for this purpose: Bernhard (1978) and Prinz (1983) report on a vertical asymmetry in visual searching and in scanning commercial ads which at least to some extent is attributed to general reading habits (from top to bottom). Other studies however showed a "modality effect" when picture and text were presented simultaneously (e.g. Witt, 1977): According to these findings the picture component always will be looked at first, no matter whether it is placed in the top or in the bottom section of the displays. They also state that a text receives more visual attention (number of fixations) when it is placed below a picture instead of above. These results are in contrast to findings from text reading which in general ascribe greater attractiveness to the top parts of a display. However, pictures in all of these studies were neither informative nor at all related to the task explicitly set to the subjects. Also recall or identification tests were applied exclusively with respect to the information contained in the text.

Thus, data at hand have to be regarded as being either confusing or insufficient with respect to our problem: One cannot predict whether subjects will reveal a top-to-bottom strategy or a modality effect in favour of the picture component, when they are confronted with a vertical arrangement of picture and text in which both are meaningful and task-relevant.

Our second experiment studied the effect of vertical arrangement on mutual interactions of acquired reading habits with assumed picture preference. Results again were compared to subjects' success in generating the required motor action plan. Also in this study possible effects due to developmental changes were taken into account: Children generally are expected to prefer pictures rather than text in visual scanning, since cognitive heuristics for generation of redundancy from language features are not fully at their disposal yet (Hussy, von Eye, & Funke, 1979). Thus neither scanning habits nor learning results obtained from adults may apply to children. As we do not know of any study of this matter, the present experiment was conducted with subjects differing in age and level of cognitive development.

METHOD AND PROCEDURE

Subjects were two groups of children aged 9 to 14 years ($N_1 = 28$; $N_2 = 28$) and two groups of adults aged above 18 ($N_3 = 32$; $N_4 = 32$). In each age category groups were matched with respect to their members' capacity of short-term memory. Subjects were asked to perform a gymnastics movement new to them (cf. experiment 1). To this end they were presented with two visual instructions. Thus the whole learning process was set up as a two step cycle, either step made up by a 10 s slide presentation (learning task) and subsequent movement execution. Each slide presentation consisted of a still row and a text component equivalent in meaning. Each component covered half of the slide. Picture and text were assembled vertically. This was done in two alternative versions. Each version was assigned to one of the two groups in either age category.

Visual scanning was evaluated with respect to the sequence in which picture and text were looked at for at least 1 s each. Also for each subject "fixation time" (summed fixation durations) falling on either the picture or the text component was calculated.

Movement execution was recorded on video tape. Acquisition scores were obtained by rating errors according to a predefined criterion scale. Error analysis covered recall of each single movement belonging to the criterion as well as (serial) order, timing and movement direction of these elementary components. Separate criterion scales were applied to each of the two learning tasks, which had to be accomplished subsequently for completion of the movement.

RESULTS AND DISCUSSION

Eye movement recording revealed that in both age categories a considerable number of subjects looked either at the picture or at the text component exclusively (1st learning task: adults 9 %, children 13 %; 2nd learning task: adults 11 %, children 29 %). In children, all subjects attended to the picture component, and at the same time performed significantly poorer in the memory capacity test than the others ($p<.05$). Subjects exhibiting such "unimodal" gaze patterns, in both age categories had significantly lower acquisition scores (motor execution) than those subjects covering both picture and text ($p<.05$). In children, poor acquisition scores cannot be ascribed to unimodal encoding alone, but may also depend on individuals' low capacity rates. There were about the same number of children, exhibiting either bimodal or unimodal strategies in either of the two groups supplied with alternative picture-text arrangements.

Children with low information processing capacity thus seem to confine themselves to the picture component for gathering task-relevant information. This tendency increases as capacity demands grow (2nd learning task). (Vertical) arrangement of picture and text however appears to be of minor relevance in this respect. Thus, on account of their developmental level children clearly split into two groups with respect to their scanning strategy. This will have to be considered carefully in production and implementation of visual teaching aids. In adults however, the number of subjects exhibiting unimodal gaze patterns is negligible for practical reasons.

All further calculations were conducted exclusively with data derived from subjects exhibiting bimodal gaze patterns. As for the sequence in which subjects attend to different instructional components arranged vertically on a display, data reveal a top-down strategy predominant in both age categories (cf. Table 3), while modality of such components (picture as opposed to text) appears to be of far less relevance to choice of scanning strategy. This finding is highly significant in adults ($p<.01$) and still prevails in children, although failing to reach statistical significance.

Table 3

Number of subjects exhibiting alternative scanning strategies with respect to alternative arrangements of text and picture (Data obtained in 2nd learning task enclosed in parentheses)

age category	vertical arrangement	vertical scanning strategy		total number of subjects
		top down	bottom up	
adults	picture/text	20 (18)	8 (7)	28 (25)
	text/picture	23 (19)	7 (9)	30 (28)
children	picture/text	16 (11)	8 (9)	24 (20)
	text/picture	13 (14)	12 (6)	25 (20)

Note: Only subjects included who attended to picture and text each for at least 1 s

Of these same subjects, modality-specific amount of fixation time was related to age categories and alternative picture-text arrangements. Under both treatment conditions, the adults spent more fixation time on the top as compared with the bottom section of the display. This is concordant with their top-down scanning strategy. Not so in children: Here data indicate a preference of the picture component under both treatment conditions. Yet there is a trend to equalize the amount of visual attention paid to picture and to text in the 2nd learning task. However, none of these findings could be secured statistically by means of a four way analysis of variance. This may be due to great variability between subjects.

According to our results, the sequence in which picture and text components of a combined visual instruction will be examined can be determined effectively by their vertical arrangement (provided both components are indeed attended to). In adults, the same holds true even for the amount of visual attention paid to either one of these components. In largely refuting the notion of a general "modality effect" in favour of the picture component, these results to some extent challenge earlier reports on visual scanning of teaching materials and consequences derived therefrom.

As learning results disclose however, according to the present study sequence of scanning picture and text does not affect task comprehension: No differences could be found in acquisition scores of subjects who first looked at the picture, as compared to those who first examined the text component. This holds true for children as well as for adults. With respect to instructional materials of the present kind and complexity, this finding refutes the notion of semantic discrepancy in picture and corresponding text being attached "functionally"to a certain order, in which these two components are attended to (cf. Table 4).

Table 4.

Average acquisition scores* (raw values of motor execution test) of subjects looking at picture and text in alternative serial order (Data obtained in 2nd learning task enclosed in parentheses)

age category	serial order of visual attention		total number of subjects
	picture - text	text - picture	
adults	14.9 (17.0)	14.5 (18.2)	58 (53)
children	13.9 (15.7)	13.9 (16.2)	49 (40)

* standard deviations about 3.0 (ranging from 2.2 to 4.0)

Note: Only subjects included who attended to picture and text each for at least 1 s

In all, our findings show combined picture-text instructions to be superior to unimodal materials, once subjects have reached a certain stage of cognitive development. Aiming at that clientele, this finding renders picture-text combinations compulsory in designing visual teaching aids in sports. Also, most subjects (children and adults) first scan the top section of displays, regardless of what modality is presented there, and turn to the bottom sections thereafter. However, serial order of attending to different sources of information does not affect comprehension. Therefore the actual placement of instructional components differing with respect to encoding modality seems of little importance to the designing of such teaching aids.

AUTHORS´ NOTE

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FOOTNOTES

[1] Eye movement recording was done with a Gulf & Western 1992 S cornea reflex recording system.

[2] The CS is obtained by the following equation:

$$CS = \frac{t_T - t_{uoF}}{t_T} \bullet \frac{\sum_{M=3}^{N} M \, (t_{CL(M,L-R)} - t_{CL(M,R-L)})}{\sum_{M=3}^{N} M \, (t_{CL(M)})}$$

CS	coefficient of scanning direction
t_T	total amount of fixation time
t_{uoF}	fixation time due to unorganized fixations
M	magnitude of gaze cluster
$t_{CL(M)}$	fixation time due to gaze clusters of magnitude M

$t_{CL(M,L-R)}$	fixation time due to gaze clusters of magnitude M, that are directed from left to right
$t_{CL(M,R-L)}$	fixation time due to gaze clusters of magnitude M, that are directed from right to left

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THE ORGANISATION OF BINOCULAR VISION IN CONJUNCTION WITH HEAD MOVEMENT IN FRENCH AND ENGLISH READERS OF 9 AND 10 YEARS

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As part of a comparison of the reading of 16 French children, aged 9 and 10 years, with 16 English children of the same age, recordings were made of horizontal movements of both eyes and of the (unrestrained) head during the reading of two texts. It was found that the French children made significantly (and considerably) greater use of the head than the English children in reading. Head movement was associated with poorer comprehension in the French children. Overall, binocular coordination was judged to be good in this study of reading under normal conditions.

INTRODUCTION

Eye movement studies of reading (and of other visual behaviour) have generally required the imposition of constraints on subjects with the result that the laboratory task is not obviously close to more normal tasks. In particular restraint or severe limitation of children's head movement reduces the applicability to normal reading of findings from eye movement studies. Our approach is to study reading under conditions which are as normal as possible while still being able to control and quantify the variables. This emphasis and our non-exclusive concern with eye movements can contribute both to a better understanding of reading and to better interpretation of eye movement data.

The value of integrating studies of eye movements with those of other aspects of reading seems to have been appreciated by some earlier researchers, such as Huey (1908), Carmichael and Dearborn (1948) and Tinker (1965), whose interests included the unfashionable and unfortunately named 'reading hygiene'. This included matters such as distance from the page, angle and posture for reading as well as environmental factors such as glare and ambient illumination levels. Although they have recently been neglected, these concerns seem to us to still be of importance (and have been included by one of us in his reading courses for university students; see Pugh, 1978).

However, because of technical difficulties, many eye movement studies have examined restricted reading. Recordings have been made from one eye only, with the head fixed or nearly so; texts have often been displayed in such a manner that readers have none of the freedom which they have in reading normal text over such matters as the angle between the text and the line of vision or the distance from the text. Indeed, many studies which use screen displayed text do not require the kind of close vision normally employed in reading.

In comparison with the important body of work on movements of the head related to movements of the eyes (e.g. Berthoz, 1974; Bullinger, 1980; Paillard, 1971; Schumacher and Korn, 1983; Zangemeister and Huefner, 1984; Zee, 1976), there have been few studies of head movement in reading. When the compendious North American textbooks on teaching reading mention the topic at all they seem to agree that head movement while reading is a practice to be discouraged. However, even such careful authors as Harris and Sipay (1980) do not adduce research evidence, as opposed to a priori reasoning, to support this view.

The view has some support from Petri and Anderson (1980) who found that normal readers used their eyes rather than their heads significantly more often than disabled readers to turn first to pictures which were randomly illuminated in a display, though the difference did not hold for pictures which were constantly illuminated. However, Salel and Gabersek (1975), in a study of 364 French schoolchildren aged 6 to 15 years, concluded that restraining the head had an adverse effect on reading performance. They identified five types of movement accompanying reading: of the lips, the eyelids, the facial muscles, parts of the body other than the head, and the head itself.

The role of head movement in reading has been examined in more detail in a series of studies led by one of the present writers, S. Netchine, and referred to more fully in Netchine, Greenbaum and Guihou (1984). It has been found (Netchine, Solomon and Guihou, 1981) that the head is used considerably in reading by young children who are learning to read, though much less so in normal adult reading. With the younger readers the advice, for one of the tasks, to keep the head still proved to have very little effect on the youngest readers, though older ones were able to act on it. In all cases, increased difficulty of text led to a greater incidence of head movement. Later studies (Netchine, Guihou, Greenbaum and Englander, 1983) confirmed earlier findings and found more head movement in oral reading than in silent reading and in reading a foreign language than in reading the native language.

Binocular eye movements have also attracted some research attention recently, particularly in the context of debates about the possible connections between the establishment of a fixed leading eye (often referred to as visual dominance) and severe reading difficulty or dyslexia. Gratton and Matin (1965), for example, had related various optometric test scores to reading ability but the only finding in which they placed great confidence was that tracking while balancing on a board correlated highly with reading ability; this, of course, implies that complex bilateral coordination goes with good reading ability, rather than supporting a visual deficit hypothesis. Bedwell, Grant and McKeown (1980), also used optometric tests and concluded that problems of dynamic visual control are related to poor reading ability, although the differences between good and poor readers were not clear on tests of static binocular vision except on a measure of stereopsis. Moseley (1978) was also unable to establish convincing connections between reading and spelling problems and eye-muscle imbalance except for when measures of esophoria and over convergence were combined. However, Stein and Fowler (1982, 1984) provide a theoretical explanation of why it is necessary for children to develop a stable 'reference' or 'leading' eye for reading and report that 50% of 6 year olds and over 80% of 10 year olds have achieved this. They found that instability of the leading eye was strongly asssociated with dyslexia and have carried out treatment involving occlusion of one eye to develop stability. Newman, Karle, Wadsworth, Hockly and Rogers (1985) have made a replication of the Stein and Fowler study, except that their control groups were not taken from referred populations, but have found no significant differences between dyslexics and normal readers on the Dunlop test which was used to assess whether a stable reference eye had developed.

Although the evidence is conflicting, none of the studies of binocular vision mentioned has employed eye movement recording (though both Grant and Newman have made other eye movement studies) nor have they taken head movement into account. It has seemed important to us to explore the use of the two eyes in conjunction with the head in the dynamic activity of reading both because of the light such studies can cast on reading difficulty and because of our interest in studying reading under normal conditions (Pugh, 1984).

The collaborative study, of which part is reported here, has two main aims. One is to develop a system for monitoring more aspects of the reading process than has hitherto normally been done, even if initially at least, some precision of measurement has to be forgone. The second is to examine how binocular vision in reading is related to movement of the head during reading.

The context of the research is a comparative study of, initially, a small group of English schoolchildren and a similar number of matched French schoolchildren aged about 10 years. The advantages of a comparative study are that any common findings have much greater generalisability than those based on studying children in one country only, whereas any differences will help identify factors which are psychologically central as opposed to those subject to local influences from pedagogical and other sources.

Much of the debate over initial reading, historically and recently, has centered on schemes and methods for teaching reading without much analysis of how the reading is done. For example, in Britain initial reading almost exclusively involves the child in reading aloud individually to the teacher, usually while standing at the teacher's desk (Campbell, 1981; Arnold, 1982). In France, however, initial reading is often a whole class activity and group oral reading remains important beyond the beginning stages. Such matters as how the book is held could well affect the amount of head movement, particularly if attitudes to head movement vary. It may be that the textbook views (mentioned earlier) reflect as well as reinforce a view which seems to be widely held in the English speaking world that children should be still when they read, a view which is readily enforceable when children read in close proximity to the teacher. On the other hand, the difficulty experienced by Salel and Gabersek (1975) in reducing head movements in young French readers, or even, as they note, being sure that the children understood what was meant, may be taken to suggest that the children had not been subject to strictures on this subject. Therefore, while we adopted the null hypothesis for the comparative aspect of the study that there would be no significant differences between the French and English groups with regard to use of the head relative to the eyes in reading, we could also propose that such differences as may be found would be in the direction of greater participation of the head in the reading of the French children.

On the coordination of the eyes, we expected to find good coordination in most cases at age 10, following the finding of Stein and Fowler (1984) that over 80% of children had established a fixed reference eye by this age. However, we were not sure how a normal reading situation, in which text is necessarily at a varying distance from the reader as the page is read for example, might affect dynamic binocular vision. Nor could we confidently predict whether the movements of the head would lead to changeover of the (postulated) leading eye from physical necessity at certain points in the text even among those whose vision for reading is normally well coordinated.

On the questions of comprehension and text difficulty, we expected to obtain confirmation of the findings reviewed in Netchine, Greenbaum and Guihou (1984) that, briefly, the harder the text, the greater the incidence of head movement.

METHOD

Sample

17 children from a school in the city of Paris were studied and 16 children, matched for age, in a school in Leeds. The French children (11 boys and 6 girls) comprised all those in a particular class whose parents gave permission for them to participate. In the English sample there was an equal number of boys and girls. Although records of standardised reading test scores were not available for the French children, the sample was judged by the school to be a reasonable cross section. The English children were chosen with reference to their scores on a standardised test of reading to be representative of their year group.

Apparatus

Movements of the eyes were monitored with spectacles and control equipment designed by John Haines (see Haines, 1980) using the scleral reflection method. Movements of the head were monitored by a potentiometer in apparatus described in Netchine, Greenbaum and Guihou (1984). The eye movement and the head movement equipment are fully compatible, both giving controllable voltage outputs representing known degrees of movement. The two pieces of equipment can also be used satisfactorily together from the reader's point of view and permit a good deal of freedom of movement.

The data were recorded on magnetic tape in analogue form as well as on paper using a pen recorder. Later, for analysis, the data were digitalised using a Zoomax analogue to digital converter.

Procedure and tasks

The French subjects were tested in a room at the laboratory close to their school and the English subjects were tested in a room in their school. The children were first asked about their interests, including their interest in reading and attitude to it, and were then asked to sit at a desk for the reading. The texts for reading were placed on a stand so that they were tilted at about 40 degrees above the horizontal of the desk top. In all the subjects were given three reading passages. All were taken from a French magazine for children and were on the subject of bears. For the testing in England, the passages were translated by a native English speaker with a degree in French and checked by the researchers for accuracy, similarity in tone, and for close correspondence in layout, line length and number of lines. The first passage (Text A) was of about 100 words and was for practice and to ensure that the children did not seem to feel undue stress or anxiety. The second and third passages (B and C) were a little under 20 lines and of about 250 words. The order of their administration was varied since they were chosen to be at different levels of difficulty. Text B was judged to be the easier, since C contained some detailed information on weights and heights, whereas some of Text B had already been available in Text A, which was in effect an abbreviated form of Text B. After each passage had been read, questions were asked orally and the answers noted in order to assess, on a five point scale, how well the text had been understood.

After reading the texts, a cloze test was given consisting of two items from the GAP test (McLeod and Unwin, 1970), translated for the French children, and tests were given to assess neurological and functional dominance, and for ocular preference in near vision and distance vision. Results of these are not considered here.

ANALYSIS

The classical distinction between fixations and saccades does not apply well to analysis of our data, since with the head unrestrained many ocular adjustments are made on account of movement of the head. We have initially concentrated on quantifying the more global data, especially the extent of head and eye movement from beginning to end of the line. However, it also possible to examine occurrences within a line for patterns in head and eye movements. Over a text, time series analyses can be used to examine the extent of head and eye movements from line to line.

RESULTS

Binocular coordination

From comparisons of the position of each eye at the beginning and end of the line, using time series analyses, it was difficult to find any evidence of the functioning in the dynamic activity of reading of the leading or reference eye suggested by Stein and Fowler (1982, 1984). There were some signs in certain subjects reading certain lines that one eye was more active (making more movements and sharper traces) but, overall, inspection of the records within lines suggests that most of the children had well coordinated vision in reading. If there is a leading eye, it remains, in our view, a difficult problem to designate it with reasonable certainty from eye movement records. There are technical considerations such as that even when the outputs from the eye movement equipment are balanced at one point in reading, the fact that a text is traversed leads to greater angular deflections at some points than others (cf Rodenberg, Kasteel- van Linge and Maas, this volume). There are also problems of operational definition, for it can be argued that the notion of a leading eye has often nothing to do with which eye has the greater summed movement but only with the amount of useful or fruitful movement made in relation to the task in hand. This latter is not easy to assess. Thus, while our results accord with the finding of Stein and Fowler (1982, 1984), insofar as they found generally good coordination by the age of 10 years, the results also suggest that the concept of a leading or preferred eye in the dynamic visual task of reading requires better operational definition.

So far, therefore, it has seemed most useful to compare the amount of ocular movement from the beginning to the end of each line for each eye with respect to the other and to look for variations over the reading of a text. Earlier studies of young French readers (Netchine, Solomon and Guihou, 1981) have shown variation (usually gradual increase) in head movements over a text accompanied by a gradual drift to the right of the position of the head at the beginning of each succeeding line. It might be supposed that such changes in position of the head could have a bearing on the establishment of a leading eye, favouring the left eye if the drift of the head is to the right.

In the present data, we have noted in the sample overall either lack of variation from line to line in the extent of eye movement or a trend of increasing movement which holds for both eyes and for the head also. The tendency towards increased movement can be be explained by one feature of reading under natural conditions. That is, in the normal school reading situation, with a text more or less flat on a desk, the page is closer to the reader at the bottom of the page than it is at the top; hence, to traverse the line, the eyes and head have to move through a larger angle for some lines than for others. We have not, however, found evidence that this increase leads to fluctuation or change in preferred eye, although this warrants study, particularly with younger readers.

Correlation of eye and head movements

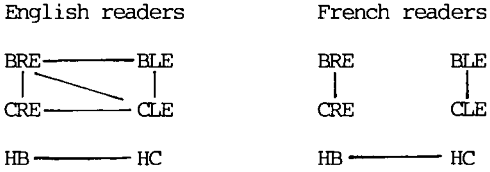
The dependent variables in the two reading tasks can be examined by correlating the mean for each subject on each text of movement of the head and each of the eyes. Correlation matrices are given in Table 1.

	BRE	BLE	CRE	CLE	BH
BLE	.60*/ .36				
CRE	.91*/ .90	-.17 /-.40			
CLE	.59*/ .46	.85*/ .93*	.77*/ .41		
BH	.14 /-.29	-.25 /-.21	-.06 /-.18	-.18 /-.02	
CH	.08 /-.15	-.04 /-.14	-.16 /-.03	-.31 /-.02	.92*/.91*

Key: RE=right eye. LE=left eye. H=head. B and C are the texts. *=p<.01.
In each cell, the English readers are shown first.

Table 1
Correlations between mean movement of head and eyes on texts B and C for the English and French readers

By clustering the significant ($p < .01$) correlations (Figure 1) one finds a similar pattern for the English readers and the French readers. The left eye, the right eye and the head are used similarly on the two texts. Thus the reading behaviour appears stable from one task to another. However, only the English readers show significant correlation between the movements of the two eyes within each of the two texts and across texts. This may be due to the greater use of eye movements as opposed to head movements in the English subjects.



Key: RE=right eye. LE=left eye. H=head. B and C are the texts.

Figure 1
Clusters of significant correlations

Extent of head movement

On both of the tasks an appreciable proportion of both the French and English children display some head movement. However, very few of the English children show more than slight movement whereas there is considerable movement among many of the French children. Overall the amplitude of head movement is significantly ($p < .05$) greater in each of the texts in the French children than in the English children (see Figure 2). From our analyses so far, this is the most striking and clearest result and is found for both texts and both orders of presentation.

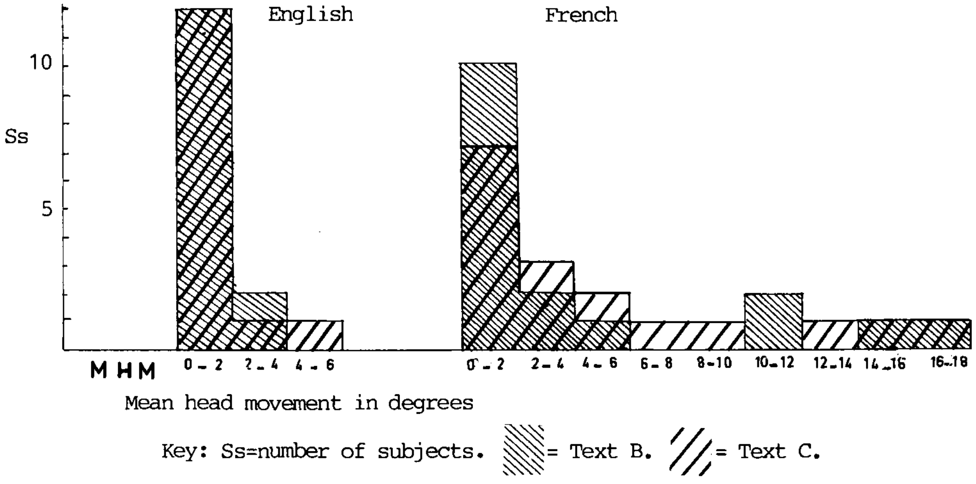


Figure 2
Mean movement of the head per line in Texts B and C: English and French readers

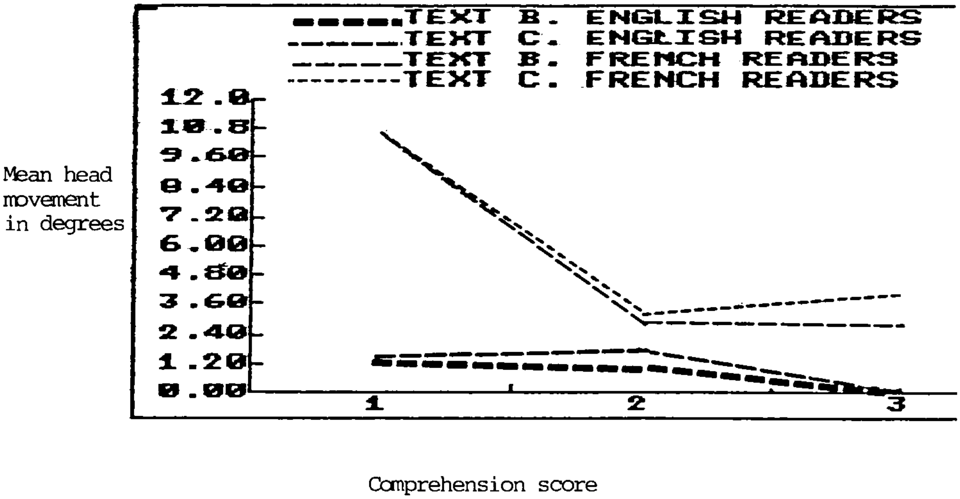
Fixations and head movements

Previous studies have examined the effect of head movements on eye movements in reading (Netchine, Greenbaum and Guihou, 1984). It is only during reading with the head restrained that the classical patterns in eye movement records are to be found. The pattern of fixations and saccades alters when head movement is involved, whether spontaneously in a young reader or through experimental manipulation, as in an adult reading text in very long lines. In both of these cases the eyes appear to be in constant movement as readjustments are made to compensate for the relatively coarse movements of the head.

Some analysis has, therefore, been made within a few lines for all subjects to test the hypothesis that the shape of the recorded fixations differs between the French and the English readers on account of the greater participation of the head among the French readers. It was found that the French readers showed a tendency towards a more pronounced negative slope within their fixations and had an average fixation duration of 319ms compared with 390ms for the English. These differences are not significant and we can note only a marked tendency for the French children to have eye movements which do not approximate closely to the classical stepped pattern but which include regressions within fixations, apparently to correct for the head movement. This question warrants further investigation with a larger sample.

Text difficulty and head movement

Comprehension score based on the assessments made of understanding shown of the texts correlated for the French children with amount of movement of the head. The coefficients of the order of -0.5 are significant $p<.05$). Those who understood less moved their heads more. This finding does hold for the English children. However, the distribution is not normal and particularly among the French children, despite the significant correlation reported, there were several who obtained the highest score while showing considerable head movement (see Figure 3).



Key: The unbroken line is Text B and the broken line Text C. The French readers are in the upper part of the figure and the English readers in the lower part.

Figure 3
Mean head movement related to comprehension score

DISCUSSION

This study confirms that it is both practicable and of value to study reading under relatively natural conditions, so that a good deal of the complexity of normal reading remains available for study, if not entirely accessible. We have found a number of stable features in the use of binocular vision and movements of the head across tasks and in readers with different socio-cultural and educational backgrounds.

In spite of much consistency, however, it is clearly found that there is much greater head movement in the reading of these French ten year olds than in the reading of their English counterparts. Various explanations could be offered for this but they break down into those based on cultural and pedagogical beliefs and those related to physical necessity. On the first, there seems to be a greater emphasis in French schools on oral and public reading. The view referred to earlier on supposed ill effects of head movement on reading may be influential (or representative) in English speaking countries. An explanation with a physical basis and which we consider is probably of more importance is that French children normally read at their desks, with the text at an unsuitable angle and distance, whereas books are often hand held by early readers in England. In consequence, it is easier for the English children to achieve an optimum distance and a suitable angle for reading. The greater use of oral reading in French schools would also be likely (Netchine, Greenbaum and Guihou, 1984) to lead to more head movement. These suggestions warrant further study.

Although we found no clear evidence on the question of eye dominance and of preferred eye, the matter should not rest there. The treatment of occluding an eye for several months is sufficiently severe for its bases to be adequately researched. Furthermore, we suspect that some of the problems attributed to lack of preferred eye might well be explicable in terms of how readers physically address the page.

It was found that the poorer comprehenders showed more head movement, even though no effects of fatigue or difficulty of text were discovered. The effect of head movement on the visual behaviour of readers within lines needs to be examined more thoroughly. It seems that the poorer readers may well have a distinct disadvantage, and such a disadvantage would be of particular importance at this stage which has been established (Neville and Pugh, 1982) as a critical one in the development of reading fluency and silent reading. However, it would also be useful to examine in detail the eye movements of good readers who also make marked use of head movement. We found several of these, especially among the French children.

Finally, whereas the literature so far has largely concentrated on reading within lines, we consider that the progress of reading over a page warrants much more attention. In particular we propose to examine further the effect of drift of the head during the reading of a page on the visual behaviour within different lines. One question which needs to be asked about this is whether the supposed predominant preference for the left eye is, in fact, neurologically determined or whether it is more to do with the mundane practicality of coping with a text written from left to right which requires greater angular deflection of the eyes and often the head as one reads down it. In young readers, especially, it would be well worth examining how the way in which they use their heads and eyes in reading a page relates to their behaviour on tasks outside reading.

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INFANT SACCADIC EYE MOVEMENTS DURING HABITUATION TO A GEOMETRIC PATTERN

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Eye movements were recorded from 12 infants aged between 4 and 6 months as they habituated to a two-dimensional geometric pattern. No significant age effects were observed on a variety of parameters of oculomotor activity. Fixations tended to concentrate on informative parts of the display, with frequent refixation of a few features. There was no evidence for the orderly, exhaustive exploration of the entire pattern predicted by some models of infant perception. There was some evidence that infants built up expectations about invariant properties of the pattern during prolonged exploration.

INTRODUCTION

Much of what is known about the infant's capacities for discrimination, learning and memory has been derived from studies using fairly gross behavioural measures, such as the consistent preference for one of a pair of stimuli differing in some critical dimension or habituation and recovery of the orienting reflex (cf Banks & Salapatek, 1983; Olson & Sherman, 1983). The habituation paradigm, for example, has been used to demonstrate recognition memory for simple forms at birth (Slater, Morison & Rose 1982, 1984) and for compound forms in infants over 3 or 4 months (cf Dineen & Meyer, 1980; Milewski, 1979; Vurpillot, Ruel & Castrec, 1977). Although infants over 5 months show evidence of recognition memory following familiarisation periods of only 10 or 20 seconds, this memory decays rapidly unless more prolonged exposures are given (Cornell, 1979; Rose, 1981; Rose & Slater, 1983).

This apparent fragility of memory following brief exposures could be a problem of retention, but could also result from incomplete exploration or point to the need for rehearsal - raising the question of the role of oculomotor activity in pattern perception. A simple model might equate line of sight and locus of attention - where what is 'seen' is the sum of what has been 'looked at' (with the fovea). In adults, cognitive skills may allow attention to be directed over an area much larger than that subtended by the fovea, obviating the need for eye movements. One might suppose this to be less probable for the developing infant, but in over 10 years of research on infant eye movements, the relationship of saccadic eye movements to information processing has not explicitly been tested (but cf Bronson, 1982a). Published studies have tended to investigate either oculomotor control per se (eg Aslin & Salapatek, 1975; Hainline, Turkel, Abramov, Lemerise & Harris, 1984; Salapatek, Aslin, Simonson & Pulos, 1980), or have been descriptive, often with an implicit assumption that because the infant makes eye movements, these must reflect shifts of attention and, therefore, information processing.

A problem of interpreting saccadic eye movements as evidence of cognitive activity during the first three or four months after birth (and probably later) is that dramatic maturational changes occur in the visual system. Although infant saccades seem motorically to resemble those of adults by one month (at least some of the time) (Hainline et al, 1984), the fovea, visual pathways and striate cortex are immature at birth and undergo significant development during the first 3 or 4 months (Abramov, Gordon, Hendrickson, Hainline, Dobson & Labossiere, 1982; Banks & Salapatek, 1983; Bronson, 1982b). The infant under 3 months is sensitive to only a fraction of the visual information available to adults, although her vision is adequate for the perception of large, near, contrasty objects like faces (Atkinson & Braddick, 1978; Banks & Salapatek, 1983). If central vision does not offer the same resolutional advantages to the young infant as to the adult or child, it is possible that eye movements serve very different functions at different ages.

There have been surprisingly few studies of oculomotor activity in infants over 3 or 4 months of age, when maturational limitations may be waning and when careful naked eye observations have shown the infant to be actively engaged in the process of discovering its environment as well as its own body (Gesell, Ilg & Bullis, 1949; Piaget, 1953). A recent study by Bronson (1982a) has suggested that it is only after 3 months that oculomotor activity shows evidence of selectivity and organisation, with repeated scanning of a few elements in a multi-element display. According to Bronson, this would be an effective, albeit redundant, means of establishing what is invariant in a pattern without the need for exhaustive exploration.

The present study was an initial attempt to investigate some of the predictions arising from models of infant habituation, namely:- (a) that, on successive trials, attention is directed first towards the most salient features and, progressively, towards less salient features or (b) that there is a need for rehearsal and/or the establishment of stimulus invariance through repeated scanning of the same features. At the same time, normative data on oculomotor activity at these ages is lacking.

SUBJECTS

Subjects were 12 infants, (7 females and 5 males), in two age-groups of six subjects each:
(a) 4-month-olds, (median age 18 weeks, 3 days; range 17 weeks 3 days to 18 weeks 5 days; two boys and four girls)
(b) 5 month-olds, (median age 21 weeks, 4 days; range 20 weeks, 4 days to 24 weeks, 2 days; 3 boys and 3 girls). The eldest subject in this group, a female, was in fact just over 6 months old at the time of testing.
All births had been full-term without complications. Where possible, infants were tested shortly after they had been fed.

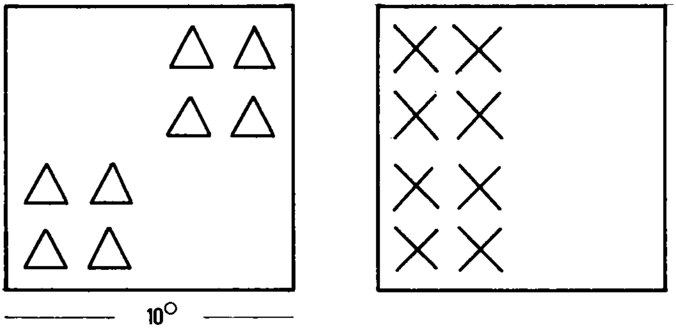
APPARATUS

Subjects were seated upright on a slightly reclining infant seat which could be raised or lowered, to bring the subject's right eye to camera height.

Eye position was calculated 50 times per second using an on-line infra red tv oculometer developed by Cambridge Electronic Design and a research team at the University of Oxford, Department of Experimental Psychology. Resolution of this system is about 1 degree vertically and 0.5 degree horizontally and accuracy is within 2 degrees for adults. Individual calibration data were obtained for infant subjects using static 2 degree diameter targets, to give an estimate of the offset between optic and visual axes. Following extensive calibration trials, a constant multiplicative gain term was used for all analyses. Algorithms which yielded the best fit for calibration data were used for analyses of data from experimental sessions. Partitioning of the data stream into movements and fixations was carried out off-line using a pseudo-velocity algorithm.

STIMULUS PATTERNS

Stimuli were two black-on-white geometric patterns based on a 4 x 4 grid presented as rear-projected transparencies (see figure 1).



Familiarisation

Dishabituation

Figure 1 The 'familiarisation' pattern consisted of eight small triangles in groups of four arranged in diagonally opposite quadrants of a surrounding square frame with sides subtending about 10 degrees. The 'novel' pattern differed from the familiarisation pattern in both the design of the constituent elements and in their overall configuration.

PROCEDURE

An 'infant control' procedure was used, with trial length determined by the infant. The familiarisation pattern was presented until the infant looked away for more than 2 seconds. The subject's attention was attracted back to the stimulus area with a flashing pattern and the familiarisation stimulus presented again. This procedure was repeated until the mean looking-time on three consecutive trials fell below 50% of the mean looking-time for the first three trials. All infants therefore had a minimum of six trials. Once the criterion of habituation had been reached, the 'attention getting' stimulus was presented, followed by the 'novel' stimulus on two consecutive trials, the length of each being determined by the infant, as for familiarisation trials. If the looking-time on at least one of these two trials exceeded the (habituation) criterion, the infant was said to have dishabituated.

RESULTS

All 12 subjects reached the criterion of habituation and 10 subjects showed recovery of attention when the novel stimulus was presented. Neither age nor total time to criterion distinguished the two subjects who failed to react to the novel stimulus from the other subjects. The median sum of fixation durations up until the criterion was reached, for both age groups combined, was 34.12 seconds (range 10.04 - 68.96 secs). This is a more precise, but more conservative measure of 'looking time' than that conventionally used in habituation studies. On the whole, there were no age effects on a variety of parameters.

Trial lengths varied both within and between subjects, whilst the total number of trials to criterion varied between subjects. No subjects showed a monotonic decline in looking-time over successive trials. Before looking at changes in parameters of oculomotor activity over time, it is interesting to consider some of the global aspects.

Distribution of fixations

Saccades between adjacent elements of both stimuli were clearly distinguishable and the change of pattern, following habituation, generally elicited an appropriate and well-defined change in scanning (Figure 2).

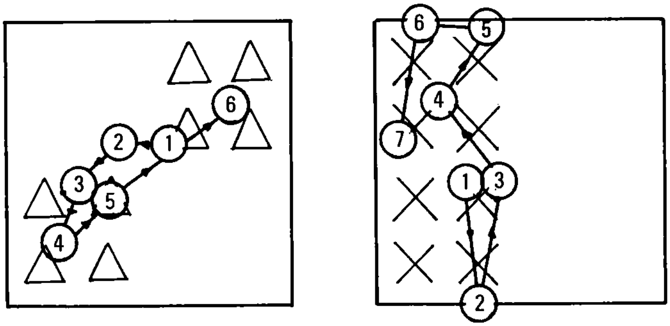


Figure 2 Scanning by a 5-month-old infant during the initial presentation of the familiarisation pattern (left) and the initial presentation of the dishabituation pattern (right).

For the familiarisation pattern, over 75% of all fixations, for both age groups, fell within the central stimulus area, allowing a 3 degree border on all sides. Of these fixations, the majority, for both age groups, fell in the two quadrants containing the small triangles. Means and standard errors are shown in figure 3a. For the dishabituation pattern (Figure 3b), only the 4-month olds tended to fixate quadrants with elements significantly more often than the empty quadrants (Binomial tests). The 4-month olds reacted to the novel pattern by an increase in attention to the top left quadrant - which was empty in the familiarisation pattern, but now contained elements. The 5-month olds were less consistent, but two subjects continued to look at the top right hand quadrant as well as the top left. The bottom right quadrant, empty in both stimuli, attracted few fixations for either age group and for either stimulus pattern.

The two subjects who failed to dishabituate were from the older age group. One subject concentrated the majority of his fixations in one quadrant (bottom left), whilst the other scanned both quadrants containing elements about equally. These data do not allow us to predict the likelihood of dishabituation from scanning during the familiarisation period.

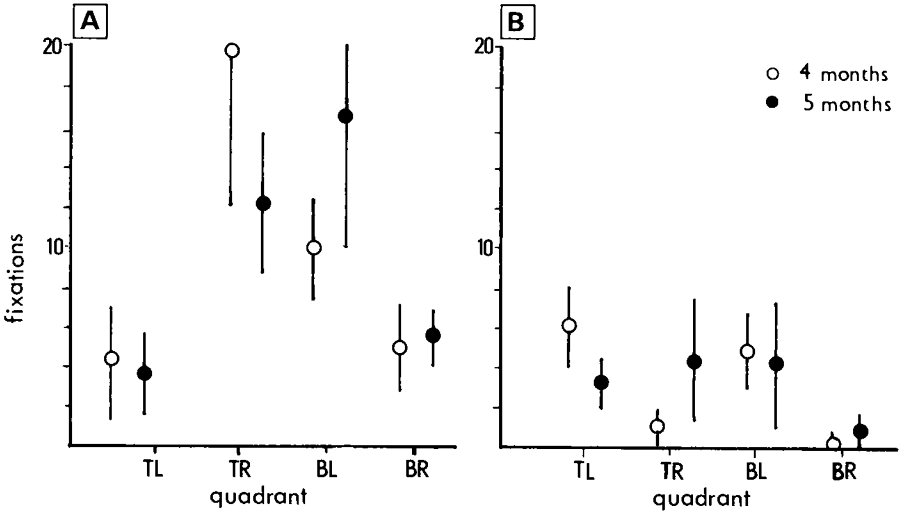


Figure 3 Mean total number of fixations in each of the four stimulus quadrants for the familiarisation pattern (Fig. 3a) and the dishabituation pattern (Fig. 3b)

Repetitiveness of scanning

One of our central questions was whether the centre of gravity of fixations shifts progressively over the stimulus on successive trials, or whether scanning was equally distributed over the stimulus on all trials, with repeated fixation of the same features. Since total exploration time varied between subjects, each subject's protocol (to criterion) was partitioned into 5 periods of equal duration.

The central 16 degree square stimulus area was divided into 64 (8 x 8) 2 degree squares and the number of fixations falling in each cell computed for each subject, in each 20% time interval. Of the 64 cells, only about one third had attracted fixations by the time the infant had habituated, for each age group (median number of different cells fixated was 24, range 12 - 28 for the 4-month olds; median = 20, range 11 - 29 for the 5-month olds). This 'economy' of fixations was largely due to the concentration of attention on the 32 cells assigned to quadrants with elements.

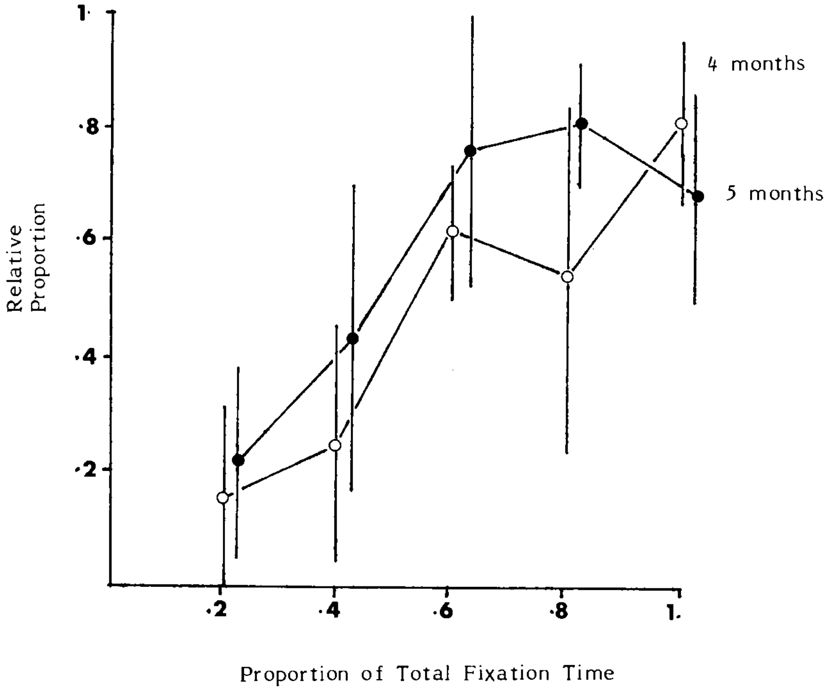
About one third of all cells fixated were looked at in the first 20% of the total exploration time (median proportion = .364, range .036 - .417 for 4-month olds; median = .322, range .238 - .545 for 5-month olds). Exploration thereafter followed a law of rapidly diminishing returns for subjects of both age groups, in that fixations were concentrated on parts of the stimulus fixated early on, with relatively few 'new' cells being discovered (Figure 4).

For every subject the most frequently fixated quadrant, overall, was one containing elements. For 11 out of the 12 subjects, the most frequently fixated quadrant during the first half of exploration also attracted most fixations during the second half. On a quadrant basis, then, scanning was highly repetitive.

Scanning patterns

The actual patterns of scanning during familiarisation varied considerably between subjects and across trials for a given subject. Three broad forms of scanning appeared, however: (a) 3 or 4 fixations on every trial except the last three; (b) few fixations on initial trials, followed by one or two trials of intense exploration lasting several seconds; (c) intense exploration for the first 3 or 4 trials, followed by brief looks at the pattern for the final 3 or 4 trials.

Fig. 4 Mean Proportion of Fixations on Previously Fixated Cells



Considerable attention has been devoted in the literature to infants' sensitivity to overall pattern configuration as opposed to the form of elements comprising the pattern. In the present study both of these dimensions varied between the two test patterns, but the data reveal two complementary forms of scanning in most subjects, for a given pattern, which suggest that local detail (eg within a quadrant) and configurational information (eg between quadrants) were derived in different ways.

When only quadrants containing elements were considered, only 5 out of the 12 subjects distributed their attention equally between the two quadrants (there were no significant age effects). For the remaining seven subjects, there was a significant tendency to concentrate on one of the two quadrants, with these subjects spending about three times as much time in the preferred quadrant compared to the less often fixated quadrant.

When data from all subjects were pooled, it was rare to see a period of exploration within one quadrant (ie. 2 or more consecutive fixations) followed by a period of exploration in another quadrant on the same trial. In fact, this ocurred on only 7 out of 74 occasions when between-quadrant saccades were made. It was more common for a single fixation to be made in the second quadrant and, on 28 occasions, the previously fixated quadrant was then returned to. Exploration on a given trial was therefore, on the whole, either 'within quadrant' or a matter of scanning rapidly between quadrants, but rarely were the two coordinated.

Recursive scanning between adjacent quadrants, was relatively infrequent, but in 7 cases double 'out-and-back' (or A-B-A-B-A) sequences were observed, and in two cases, there were 3 repeated 'A-B-A' sequences. This pattern of repeated fixation between adjacent locations also occurred within quadrants and has been observed very frequently in other data from stimuli with discrete elements, particularly in older subjects (5 and 6 months).

Stability of oculomotor activity

Fixation durations were remarkably stable, with a modal value of 180 msec, when both age groups were pooled. The mean fixation duration was 243.9 msec (sd = 163.8) for the 4-month olds and was 282.0 msec (sd = 179.2) for the 5-month olds. Despite the overall stability, the range of fixation durations was large, varying from 80 msec to 2.5 seconds, although less than 15% of all fixations lasted longer than 600 msec. Median fixation durations over the course of habituation are shown in Figure 5.

When both age groups were pooled, saccade amplitudes had a modal value of 2.5 degrees. When within- and between-quadrant saccades were considered separately, the former had a median value of 2.5 degrees (range 0.49 - 6.0 degrees), whilst between-quadrant saccades had a median value of 3.5 degrees (range 1.2 - 11.0 degrees). Between-quadrant saccades tended, then, to be only slightly larger, but their amplitudes were more variable. Large amplitude saccades (over 9 degrees) tended to take the gaze outside the stimulus area and were somewhat more frequent towards the end of trials and during the final 20% of exploration. This is consistent with a tendency for the infants to become more agitated as they habituated. Median saccade amplitudes over the course of habitation are shown in figure 6.

Figure 5 Median Fixation Durations

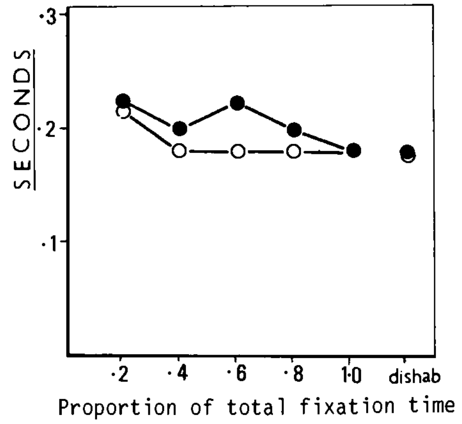
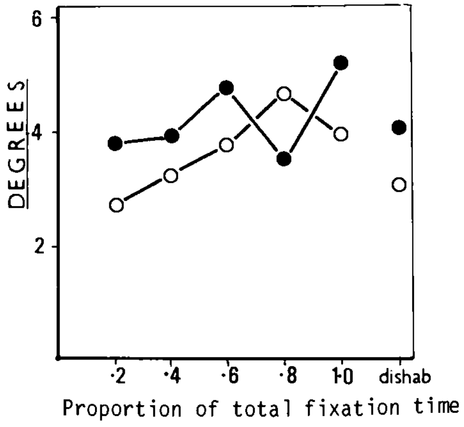


Fig 6 Median Saccade Amplitudes



●4 months ○5 months

DISCUSSION

How might the infants' oculomotor behaviour be related to underlying cognitive activity? The observation that all but two or our subjects actively scanned the 'novel' pattern, whilst the last few presentations of the 'familiarisation' pattern received only cursory inspection, suggests that habituation was indeed an effect of their recognition that the familarisation pattern was 'the same thing' on successive presentations. How, then, was their scanning related to this process of recognition?

As both overall configuration and form of stimulus elements varied between familiarisation and novel patterns, it was not possible to determine the basis for discrimination (or failure to discriminate). The change of elements, from crosses to triangles or the change of overall configuration could each have been sufficient to indicate the change. Clearly, if a few brief glances at the familiarisation pattern were sufficient, on the last trials, to inform the infant that 'it was still the same thing', a few brief glances would also logically be sufficient to indicate that the novel pattern was 'something different'

In other words, when the change of pattern is big enough, lengthy exploration would seem to be the result of a discrimination, not its mediator. This would make the relationship between looking time and discrimination less obvious than has been assumed. This would accord with the findings of Rose & Slater (1983) that brief exposures are sufficient to permit discrimination of simple and very different patterns by infants of the ages tested here. Even so, our subjects made, on average, 3 or 4 fixations even on the last (criterion) trial.

So what of the process of habituation itself? The data suggest that attainment of the criterion of habituation was not a matter of terminating exploration once all parts of the pattern had been scrutinised. There was also no evidence that less 'salient' features attracted increasing attention as exploration proceeded. Rather, exploration was highly repetitive, with a few locations being returned to often. This could imply some form of 'rehearsal', with the gradual build-up of expectations about the consequences of making a given eye movement. In some rare, but nevertheless noteworthy cases, adjacent elements or quadrants were scanned by repeated back-and-forth alternations of gaze. This would be an efficient, although redundant, means of establishing the overall configuration of the pattern or the configuration of elements within a quadrant.

The high proportion of relatively brief fixations may indicate that, much of the time, very little 'information processing' was going on, at least beyond the first few trials. Shorter fixations became more frequent over the course of habituation, especially for the younger subjects. There was also a tendency for large amplitude (over 8 degrees) saccades to become more frequent as the infants habituated. Both of these results may be related to our observation that subjects became more agitated as they habituated. These large amplitude eye movements were not directed at any particular target and were in marked contrast to the fine control shown when infants explored the pattern itself. As such they may have had affective, rather than instrumental origins.

At this stage we can only speculate about the relationship of saccadic eye movements to cognitive activity in infants - indeed, this relationship is far from clear even for adults. For the infant, there is no experimental 'task'; the regularities of the world may only be abstracted with a great deal of active exploration and experimentation. Given the maturational changes occuring in the visual system, it may also be necessary for the infant to look in order to explore the changing properties of its oculomotor system (cf Bullinger, 1981). In this case, objects may become what Piaget called 'aliments for looking'. With major postural changes taking place throughout infancy, the possibilities for oculomotor control may also change significantly, bringing with them the kinds of 'revolution' in the relationship of sensorimotor activity to cognitive activity described by Mounoud (1982).

These data suggest then, that by 4 or 5 months, looking has certain instrumental characteristics which mediate recognition of simple, multi-featured objects. The fact that cognitive 'instruments' are developing in tandem with sensorimotor instruments makes it unlikely that models of oculomotor functioning developed for adults may be transferred to infants. A more profitable approach may be to treat infant oculomotor activity not as an autonomous behaviour, but as sharing certain functional principles with other sensorimotor systems at a given age or level of cognitive development. One such property apparent in infants may be the repetition and reversibility of actions as a means of establishing invariance.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

SYMMETRY CATCHES THE EYE

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Eye movements of ten adults were recorded as they judged the aesthetic potential of the original and altered single and double symmetrical transformations of five structurally complex abstract compositions. It was found that when symmetry was present, both survey and examination fixations were concentrated along the axis of symmetry. When symmetry was absent, however, exploration was more evenly distributed to all areas of the stimulus array. Although symmetry influenced the spatial aspects of exploration, the number of survey and examination fixations used to explore the arrays was not influenced by the presence of symmetry. Results are discussed in terms of a two-step symmetry encoding model and Berlyne's theory of aesthetic behavior.

INTRODUCTION

A wide range of evidence shows that symmetry is an important primitive or primary unit of visual pattern analysis which influences the encoding of a visual array. Interpretations of this "symmetry effect" have consistently resulted in a two-step symmetry encoding model (see, for example, Freyd & Tversky, 1984). In general, these models all propose that, with the onset of a stimulus which contains perceptually salient symmetrical features, there is an immediate, effortless sensing or detection of the symmetry. It is this preattentive, global impression of the stimulus which then preprograms the serial scrutiny of features to take advantage of the redundant nature of the relationship among local features of a symmetrical array.

Despite the fact that symmetry has been a frequent experimental variable in studies of form perception, most of the evidence supporting this symmetry encoding model is indirect, i.e., it is based on performance outcomes in symmetry detection and recognition tasks. Very little attention has been paid to the encoding processes which mediate the evaluation and performance effects due to symmetry reported in the literature. Research from our laboratory and that of Llewellyn-Thomas provides the only direct evidence that symmetry does, in fact, affect visual scanning behavior.

We (Locher & Nodine, 1973) observed that the eye movements of subjects examining random shapes which subtended 36° horizontally were concentrated on one side of the axis of symmetry of symmetrical shapes while the distribution of fixations for asymmetrical shapes did not exhibit these one-sided scanning patterns. Llewellyn-Thomas (1963) also reported the presence of one-sided scanning strategies in the fixation patterns of subjects viewing the Rorschach inkblots. We speculated that these one-sided fixation patterns for symmetrical shapes were the result of an encoding strategy suggested by a preattentive global response to the overall configuration of symmetrical shapes.

The present research sought additional evidence of a symmetry effect on perceptual encoding by demonstrating that the redundancy among elements of symmetrical arrays is reflected in the exploratory strategy used to encode these arrays. Our previous research (Locher & Nodine, 1973) provides only limited evidence of the utility of symmetry in visual encoding because the stimuli used were black and white nonsense shapes which did not contain a high degree of structural complexity. Furthermore, the findings are limited by the accuracy of the eye movement recording devices and scoring techniques available when the research was conducted over a decade ago. In the present research, a computer system was used to record and score eye movements of subjects who examined the original and symmetrical transformations of large, color, multidimensional abstract compositions. The general purpose of the present research was to see if support for the symmetry effect explanation of encoding outlined above could be found in the scanning patterns of subjects viewing these artworks. In addition, analyses of the spatial and temporal aspects of aesthetic exploration of these compositions were examined guided by hypotheses generated from Berlyne's theory of aesthetic behavior.

STIMULI

The stimuli were constructed from five abstract paintings: Hans Hoffman's "The Golden Wall" (1961, Chicago Art Institute), Marcel DuChamp's "King and Queen Surrounded by Swift Nudes" (1912, Philadelphia Museum of Art), Paul Klee's "Roseraie" (1920, Galerie Beyeler, Bale), Piet Mondrian's "Composition with Red, Yellow and Blue" (1939, The Tate Gallery, London), and Jackson Pollock's "Seven" (1950, C. Cardazzo Collection, Venice).

Color photographs of each of the paintings were digitized using a DeAnza image-array processor serviced by a LSI 23 computer. Each of the stored images was transformed by either: (a) reflecting the left half to create a symmetrical image about the y-axis, or, reflecting the bottom half to create a symmetrical image about the x-axis, and (b) reflecting the bottom-left quarter to create a symmetrical image about both x- and y-axes. The resulting images from one of these symmetrical transformations are shown in Figure 1.

Figure 1
Marcel Duchamp's "King and Queen Surrounded by Swift Knights", original version (left), single-symmetry version (middle) and double-symmetry version (right).

All five original artworks were transformed about either x- or y-axis, depending on compositional structure. In addition, all but Pollock were transformed about both axes. This made a total of 14 images: five originals; five single-axis transformations; and, four double-axis transformations.

SUBJECTS AND PROCEDURE

Ten adult subjects between the ages of 20 and 30 years served as subjects. Each subject was read a standard set of instructions which described the task as one of judging abstract art for inclusion in a hypothetical art show. The subject was asked to use a 5-point rating scale to judge each artwork in which rating 1 indicated "Poor- definitely do not show it, downright boring", to rating 5 which indicated "Excellent- shows exceptional creativity and originality, definitely show it". Subjects were told that they would see a total of 14 artworks and that each would be presented for a maximum of 12 sec, but that they could terminate the display as soon as they made a judgment. The instructions indicated that some of the paintings would look similar compositionally because they were done by the same artist, but that this should not affect their judgment; they should judge each artwork on its own merits. The ratings were given aurally after the display terminated.

Subjects were seated in front of a color TV monitor. Their head was placed in a head-and-chin rest and the eye-movement glasses (Gulf & Western, Model 1200) were fitted. The art images were presented in a constrained, counterbalanced order on the TV screen which was 76 cm away. Since the images were 25 x 25 cm, the display subtended a total visual angle of approximately 19^{o}. Calibrations were carried out before and after each image was presented. The pre-calibration data were used to correct irregularities in the spatial alignment of the axis of gaze as the subject fixated each point in the 3 x 3 array of calibration points. This correction was applied to the eye-movement records produced during scanning of the artworks. The post-calibration data were used to check for head movement between pre- and post-calibration (Carmody, Kundel, & Nodine, 1980). Forty-two eye-movement records from three subjects were eliminated because either pre- or post-calibration data exceeded 2^{o} visual angle. Analyses were performed on the remaining 98 eye-movement records of seven subjects viewing 14 art images.

RESULTS AND DISCUSSION

The first question asked by this research was, to what extent does the collative force of symmetry guide exploration? Does the spatial distribution of fixations over the art vary as a function of whether symmetry is manipulated about the x-axis, y-axis, or both axes? An examination of subjects' scanning patterns, and the results of two symmetry detection investigations, indicated that an analysis of one-sided strategies like that reported in Locher and Nodine (1973) would be too insensitive to the effects of symmetry upon the spatial distribution of fixations. Barlow and Reeves (1979) have shown that the symmetry in random dot displays is best detected when next to the axis of the display. And Bruce and Morgan (1975) report that violations of symmetry are more readily detected when they occur close to the axis of symmetry. The force of the axis of symmetry on attention noted by these researchers can be seen very dramatically in Figure 2. It is very clear from these patterns that a simple analysis of one-sided patterns would fail to detect important symmetry effects upon exploration.

To analyze the change in sampling distributions as a function of increasing symmetry, we measured the proportion of fixations which fell into the following areas of each art image: x-axis, y-axis, and background. The x and y axes were defined by bands that were 6.7 cm or 5^{o} wide. The background consisted of the

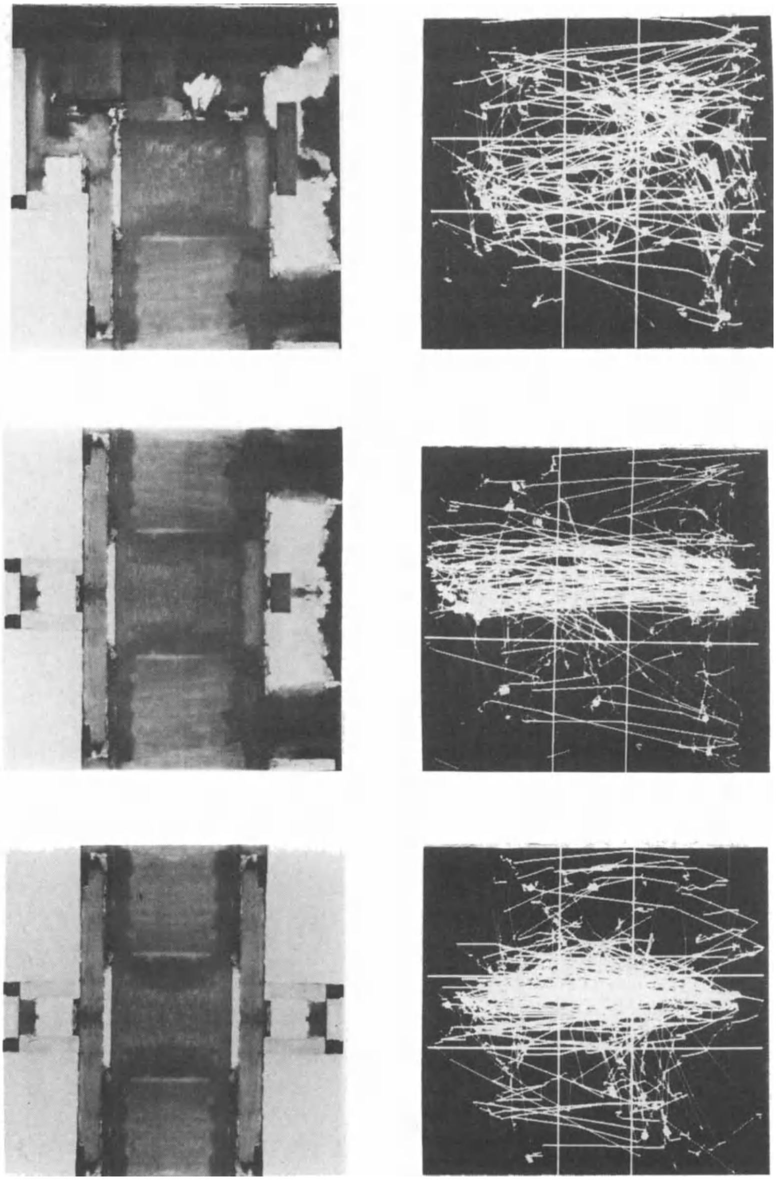

Figure 2
Artworks (left column) and composite fixation patterns (right column) showing survey fixations (lines) and examination fixations (dots) for the original Hoffman (first row), and its single-symmetry (second row) and double-symmetry (third row) transforms.

four leftover areas which were approximately 9 by 9 cm or 6.6° each (see Figure 3). If symmetry attracts the eye, then when the original art images are transformed, fixations should fall along the appropriate (x or y) axis of symmetry depending upon the nature of the transformation. One might argue that whether or not the axis of symmetry attracts the eye depends on the contents of the art image. We deliberately chose abstract works to reduce references to representational objects which are easily picked up when symmetrical transforms are applied. However, some of our artworks, in particular those by Duchamp and Klee, contain representational forms. We will discuss the implications of this as we present the results.

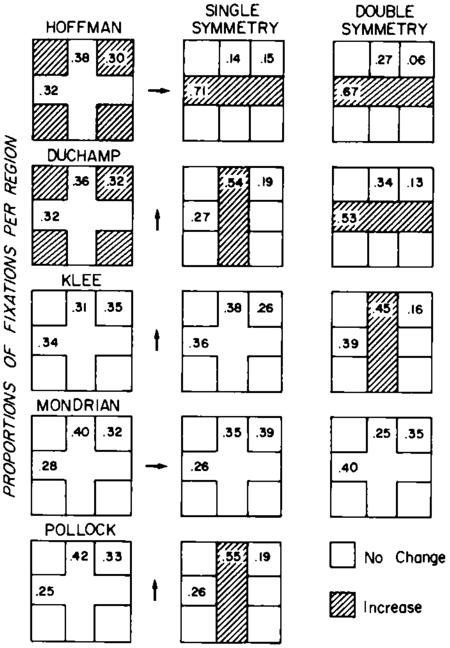

Figure 3
Proportions of fixations per region (x-axis, y-axis, and background) for all originals and their single and double symmetry transforms. Diagonal shading indicates significant differences in proportions compared to the original. Differences were tested by F test. Arrows indicate direction of axis of symmetry.

For each of the three template regions for each art image, the proportion of all fixations for the first 3-sec viewing period and the proportion of all fixations taken over the entire 12-sec viewing period were measured. The proportions of all fixations for the first 3-sec period are presented in Figure 3. Analysis of variance was used to compare the distributions of fixations among the original, single-symmetry transformation and double-symmetry transformation of each artist. A significant difference in the proportion of fixations falling in a given region across transformations is indicated in Figure 3 by the diagonal line shading of that region. Thus, for example, there is a significantly higher proportion of fixations that fall on the background of the original Hoffman than either level of symmetrical transform. However, when an x-axis symmetry transform is applied to the Hoffman a significantly higher proportion of fixations fall along the x axis. Significantly more fixations fall along the x axis also when a double-symmetry transform is applied. A similar pattern is found for Duchamp, except the manipulated single-symmetry transform was about the y axis, and fixations increased correspondingly along the y axis. In fact, proportions increased in the same direction as single-symmetry manipulations of the original art images for three of the five artworks: Hoffman; Duchamp, and, Pollock. The results for the double-symmetry transforms show increases along the x axis for two art images, Hoffman and Duchamp, and increases along the y axis for Klee. No changes were observed as a function of symmetry transforms for Mondrian. Similar findings were obtained using the proportions for all fixations over the entire 12-sec viewing period.

The pattern of results shown in Figure 3 supports and expands on our earlier findings with nonsense shapes and is consistent with the two-step symmetry effect explanation of encoding of symmetrical shapes outlined in the Introduction. These results demonstrate that the eye detects the axis of symmetry during the first few seconds of viewing and uses this axis as a base of operations for sampling details within the image. When symmetry is present and detected, exploration is concentrated along the perceived axis of symmetry. Without symmetry present, as in the originals, exploration expands to background areas (especially Hoffman and Duchamp).

The responses of the eye to the double-symmetry displays are somewhat more puzzling and therefore more speculative. In the double-symmetry manipulation the lower left-hand corner of the original art image was reflected about both x and y axes into the remaining three quadrants of the image. Whether this double-symmetry transform leads to an x- or y-axis bias in the spatial distribution of fixations will depend on the content of the lower left quadrant of the original. If there are shapes, colors or lines that hug either x or y axis (or both), these will be reflected such that they will create artificially new structures in the image that may attract attention. For example, when the lower left quadrant of the Hoffman is doubly transformed, the resulting image has two dominant vertical yellow bands broken by color-form details in the center. It was these details that led to the strong x-axis bias in the fixation distribution as Figure 2 shows. The question is how this bias relates to detection of a double-symmetry transform. Where should one need to look to obtain maximum information about this double-symmetry image with a minimum of scanning? The answer would seem to be to look in the center of the image. But as can be seen in Figure 2, which shows the fixation distributions of all subjects, fixations do not cluster in the center of the image. Clearly the question of what constitutes the center or centers of a double-symmetry image needs much additional research.

Berlyne (1971) states that much of what he calls aesthetic behavior consists of intrinsic exploratory responses. He has proposed that two types of exploratory activity are prominent constitutents of aesthetic behavior--specific and diversive exploration. Specific exploratory behavior occurs when a state of perceptual or epistemic curiosity is created in an observer by uncertainty concerning the information content of an object or event. The function of specific exploration is to obtain information about the object to relieve this uncertainty. Diversive exploration, on the other hand, is used to "seek out stimulation, regardless of content or source, that has appealing collative properties" (Berlyne, 1971, p. 100). According to Berlyne, both types of exploration are influenced strongly by collative stimulus properties and both can be found in most types of exploratory activity.

Molnar (1981) has noted the similarity between the two types of exploratory behavior described by Berlyne and the two patterns of eye movements used by perceivers to examine complex scenes consistently reported in the literature (see, for example, Antes, 1974; Buswell, 1935; Karpov, Luria, & Yarbus, 1968; Nodine, Carmody, & Kundel, 1978). At the onset of a picture, an orienting period lasting approximately 2 to 3 sec occurs during which observers exhibit a survey-type scanning strategy. During this initial survey period, many fixations of short duration (approximately 200 msec) are directed to areas of high information potential presumably to identify potential targets. Fixations then become longer in duration and closer in space as the observer makes a detailed examination of informative or critical features within the display. This explanation of picture perception which has emerged from the study of the time course of picture viewing is very similar to the two-step symmetry effect explanation of encoding of complex symmetrical displays outlined in the Introduction of this paper.

To examine the temporal aspects of aesthetic exploration of the artworks in the present research, we distinguished functionally between two types of fixations: survey, characterized by short dwells, 100-300 msec, which are 3 standard errors below the mean (320 msec); and, examination, characterized by long dwells, > 400 msec. It was found that 65% of all fixations for all stimuli were short-dwell survey fixations and 18% were long-dwell examination fixations. These values for abstract works are remarkably similar to data reported by Molnar (1981) who studied the visual exploration of subjects engaged in an "aesthetic" task while viewing eight classical works by such artists as Rembrandt and Chirico. In Molnar's study, 61% of all fixations were less than 300 msec in duration as compared to 65% in the present study.

The distribution of short- and long-dwell fixations for all subjects for the original Hoffman and its two transforms can be seen in Figure 2. Note that, while the location of both short- and long-dwell fixations was influenced by symmetry as previously explained, the number of each type of fixations does not differ from one stimulus to the next. In fact, it was found that the percentage of all short-dwell fixations used to encode the original, single-symmetry, and double-symmetry artworks were 33%, 34%, and 33%, respectively.

Although the number of short-dwell fixations (and long-dwells) used to explore the displays was not influenced by the presence of symmetry, temporal aspects of exploration did change as a function of viewing time. Consistent with the picture perception literature, and the findings of Molnar (1981), the percentage of short-dwell fixations significantly decreased from 39% in the first 3-sec viewing period to 15% in the last 3 sec of viewing, $F(3, 90) = 65.25$, $p < .001$. A correspondingly slight decrease in long-dwell fixations was also noted (27% and 21% in the first and last 3-sec viewing periods, respectively). Thus, in the first 3 sec of viewing a majority of all fixations were short-dwell survey fixations and the rest were long- and medium-dwell examination fixations. We believe that the occurrence of this large number of short-dwell fixations during the initial viewing, and their spatial distribution already noted, can be taken as evidence that they provided perceivers with a global survey, a gist, of the art image. When symmetry was detected, subjects were able to take advantage of the redundant nature of symmetrical shapes and the biased scanning strategies for the symmetrical transforms like those seen in Figure 2 resulted.

Despite the significant reduction of short-dwell fixations over time, the presence of survey fixations throughout viewing indicates that they serve another function after they have provided a gist of the display. If one examines the composite fixation patterns in Figure 2, it can be seen that the artworks were explored by many survey fixations interspersed with examination fixations. In our view, the short-dwell fixations reflect what Berlyne (1971) has called specific exploratory activity and were used to obtain information about the display to relieve curiosity due to uncertainty. Periodically, when "interesting," "novel," or "pleasing" areas of the artwork were located by specific exploration, diversive exploration (long-dwell fixations) were used to examine these areas more carefully. We believe that these findings provide strong evidence to support Berlyne's hypothesis that specific and diversive exploration are important constitutents of aesthetic behavior.

Finally, to what extent were subjects' aesthetic judgments related to their exploratory activity? Because of the limited number of subjects used in this research, our data can provide little in the way of a definite answer. Nevertheless, we did observe the tendency for the ratings of interestingness to be related to the spatial distribution biases due to symmetry. For example, when symmetry in the single- and double-axis transforms functioned as the basis of operation for sampling details within the artwork, ratings for the single-symmetry and/or double-symmetry transforms were lower than for their original. Average ratings for the originals, single- and double-symmtry transforms of Hoffman, Duchamp, and Klee are 4.0, 3.3, 2.1; 4.0, 3.1, 3.0; and, 4.1, 4.0, 2.9, respectively. Apparently the regularity, or redundancy, of symmetrical displays, _if_ it is apprehended quickly and used to direct encoding, reduces the uncertainty and the corresponding disorientation. This disorientation is the basis of the triggering mechanism in Berlyne's (1971) aesthetics theory.

In summary, we have presented evidence that symmetry does affect the spatial aspects of exploration of complex visual displays. During the first few seconds of exploration of a symmetrical display, the axis of symmetry catches the eye. Having detected symmetry, the observer then takes advantage of the redundancy contained within the stimulus as viewing proceeds. This is accomplished by concentrating fixations along the perceived axis of symmetry during exploration. On the other hand, the presence of symmetry in our art images did not influence the number of each type of fixation, survey or examination. Thus, it seems that specific and diversive exploration occurred to the same degree throughout the time course of viewing for the originals and their symmetrical transformations.

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Footnote

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EYE MOVEMENTS: From Physiology to Cognition
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SOME AESTHETICAL ASPECTS OF VISUAL EXPLORATION

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The relationship between eye movements and the aesthetics of visual arts is not as simple as philosophers prior to the work of Javal imagined, it nevertheless exists.
1/ The experiment shows that, considered statistically the length of the saccades and the duration of an observer's fixations differ considerably between a "classical" painting and a Baroque one.
2/ The matrix obtained from the first fixations, considered as stochastic and Markovian, seem to be ergodic (as well). This signifies that after repeated multiplication by a matrix of transition, it will acheive a final equilibrium. The form of this equilibrium and the number of steps necessary to attain it could constitute a means of measuring composition quality.

INTRODUCTION

The French painter and scholar, Roger de Piles, probably under the influence of Descartes, demonstrated the role of eye movements in the appreciation of paintings. Strangely enough, there are very few works on eye movements connected with empirical aesthetics. Nevertheless, as soon as Javal's findings were known, aestheticians found that eye movements could be a tool of great utility for their work. In fact, they stated that when the eye explores a form or an object, the characteristics of the eye movements must be the same as those of the form or object. This means that a jagged form should be seen with jagged eye movements and a harmonious one with harmonious movements.

But aestheticians soon became disappointed. At the beginning of our century, Stratton (1906) found that the eye does not follow the line of a "pleasing curve" at all. So, the most beautiful object, or most harmonious one, will not be explored by harmonious or beautiful eye movements.

New investigations have been started in different directions, but without real aesthetic aims. Most of the results concerning aesthetics and eye movements are produced by non-aesthetically oriented research. For instance, Yarbus' work (1967) on the exploration of a picture under various instructions concerns, without a doubt, aesthetics. However the aim of his research was not an aesthetic one. Buswell's (1935) problem, how people look at pictures, was a problem of perception, producing nevertheless important data for aesthetics. More closely related to aesthetics, but perhaps less useful for real aesthetic research, are the works of other investigators like Brandt (1945) who found some rules of eye movement in advertisement and graphic design. Most of the research in eye movements, functional fovea and more generally on seeing, conducted by Hochberg (1968), was possibly more useful for aesthetic purposes than the aesthetically oriented work of Brandt.

INFLUENCE OF AESTHETIC MOTIVATION ON VISUAL EXPLORATION

We have to examine first the differences between the modalities of exploration under aesthetic and non-aesthetic conditions, if such differences do exist. Yarbus (1967) has convincingly demonstrated the role of instruction in eye movement strategy. There is nothing astonishing in Yarbus' findings. If I am asked to look at an object, I will look at it. But what happens if the curiosity of the subject is guided by aesthetic motivations ? Will the movements of his eyes be different than eye movements under ordinary conditions ?

Global study of visual exploration

In an experiment, we tried to obtain some information concerning this problem. We projected eight classical pictures (from Rembrandt to Chirico) for fourteen volunteer subjects who were students of the University (Arts Plastiques). Half of them were instructed to observe closely because after projection, they would be questioned about what they saw in the pictures (semantic group). The other students were instructed to look at the pictures attentively because they would be questioned about aesthetic qualities of the pictures (aesthetic group). Their eye movements were recorded by the method of corneal reflection (Young, 1962), combined with the method of video-tape recording. The histogram in figure 1 shows the distribution of the durations of fixations, in percentages.

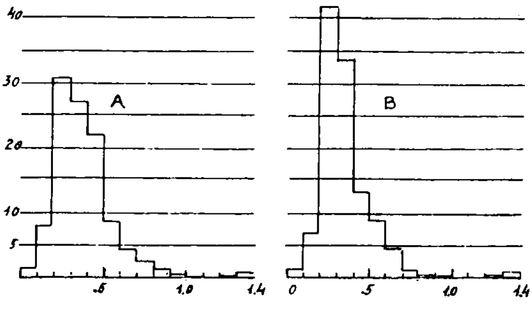

Figure 1
Distribution of duration of fixations grouped in classes of 100 ms :
(A) Aesthetic group; (B) Semantic group.

First we notice that the duration of fixation in the "aesthetic" situation (histogram a) has an outline radically different from the outline of the semantic group (histogram b). In particular, we find a greater number of fixations longer than 300 ms. in the aesthetic group. Thus, the exploration of the aesthetic group is slower than the exploration of the semantic one. We can observe this difference between the two types of exploration at the level of mean duration of fixation. The mean for the semantic group is 315 ms. and is significantly different from the mean of the aesthetic group : 365 ms (p<.01).

Concerning the spatial aspect of exploration, the results are less interesting. If we arrange the lengths of saccades by degrees in the same way as we did for the times, we cannot find any difference between the two groups. Nothing is astonishing about this as the two parameters, spatial and temporal, are two different functions and are linked to different psychological mechanisms. The temporal one depends principally on the level of interest and motivation and the spatial one depends especially on the stimulation.

Nevertheless our findings show that æsthetic motivation involves slower visual exploration. Can we be sure that this is true ? Indeed, our results are clear. But, on the other hand, it is well known that all secondary tasks given to a subject while reading, slow down the exploration. If we ask the subjects to solve some arithmetic problems, even very simple ones, the duration of fixation becomes immediately longer. This is similar in aesthetically directed picture exploration. Here, the aesthetic task given to the subject is very difficult. Our post-experimental interview indicates this. All the subjects declared that they had more difficulty with the aesthetic task than with the semantic one. Thus studying the global form of the exploration, we cannot find convincing proof of the influence of aesthetic motivation on visual scanning. A detailed study of eye movements should be more instructive.

Study of scanning

Of course, it would be interesting, from an aesthetically oriented point of view, to examine the contents of the individual fixations : the scan path. Kolers (1973, 1976) based on the results of Yarbus (1967) and Buswell (1935) thinks that the eye seeks the region of semantically rich information. This is the opinion of Gould (1973), Loftus (1974), and almost all psychologists concerned with this problem.

But the term "information" is a very ambiguous one. The specialists employ it in quite a different sense than as in common use. Shannon (1962) insists on the fact that this special sense "must not be confused with its ordinary usage. In particular, information must not be confused with meaning". If we find many fixations on any part of the picture, we cannot be sure that it is a region full of semantic information. There are numerous other perceptual variables that interfere with the strategy of exploration which can be named, legitimately, information. Can we hope that in aesthetic attitude the subject will attain, with his eyes, the part which is rich with aesthetic information ? I think so. But actually, we cannot demonstrate it. Figure 2 shows the first 60 fixations made by two subjects, one from the aesthetic group (A), the other (B) from the semantic group while looking at the same picture.

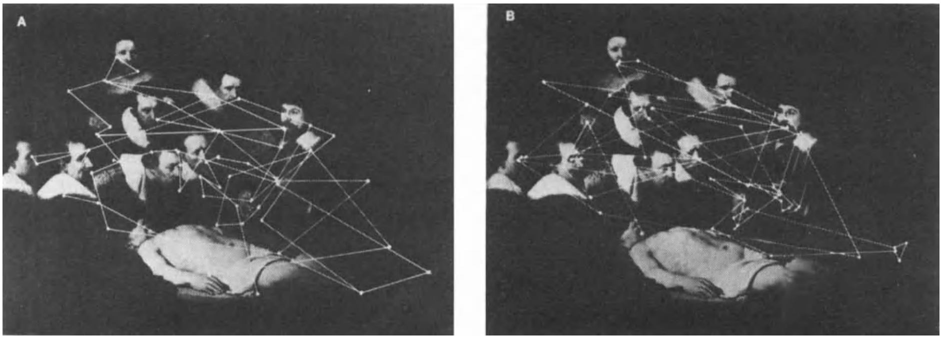

Figure 2
Graph of 60 fixations of 2 subjects :
(A) Aesthetic group; (B) Semantic group.

Indeed, there is little difference between the two explorations. The part of the picture most often looked at was nearly identical in both recordings. Most of the fixations in both pictures correspond with the heads and sometimes the hands of the persons. Therefore, they are highly correlated with the parts that are full of semantic information and are also at the same time, from a sensory point of view, the most important -the most attractive for the eyes. The most explored part of the image is the center where there is the most semantic information. We cannot know if this part of the picture was chosen because of its semantic information or as a function of its formal qualities. The greatest merit of Rembrandt is that he could combine all informative parts of the picture and manage to have the formal qualities (luminescence, colour, contrast) in the same places simultaneously.

MEASUREMENT OF COMPLEXITY

Speaking about collative variables, Berlyne wrote (1960) : "Complexity is without any doubt the most impalpable of the four elusive concepts that we are attempting to delimit" (p. 38). He added : "It is however possible to enumerate some of the most obvious properties on which the complexity ascribed to a pattern will depend". The question remains open : how to measure complexity, and if that is not possible, how at least to describe it ? As far as an artificial stimulus is concerned, there is no problem. Attneave (1957) gave experimental proof that it is the independent turns, the contour, the presence or absence of symmetry, and the mean difference between the angles of successive turns in the contour which define the complexity.

But what about complexity of natural stimuli, of all the stimulations where the experimenter has no possibility to manipulate the physical elements ? A technique often adapted to measuring complexity would be the well know "chess-board method", whereby a grid cuts up the image into a large number of small squares easily submitted to statistical analysis. This is the method of Picture Processing used by computer scientists.

When the statistician counts the frequency of a certain letter or word in a text, or of a note in a musical score, he has a well-defined temporal order; he can study the probability of one letter preceding another. In the case of a visual stimulus it is impossible to detach the elements from the whole, to categorically separate one element from another. In addition, in vision one cannot assert that one element precedes or follows another.

Discretisation by the eye

As a matter of fact, it is useless to want to break down the visual world into elements since it has already been done. The visual world is essentially discrete; its continuity is a psychological illusion. In some still unknown way our visual system fills in or supplements the discrete input to create the subjective sense of continuity (Kolers, 1973).

The visual system is a discontinuous processing system, where discontinuities are usually marked by the occurrence of "jumping eye", as it is pointed out by Gaarder (1975). Eye movements transfer pictures, a spatial phenomenon, to a sequence of temporal events. So, we don't need a method to transform continuous space into a set of discrete temporal events. The visual world is digitalized by nature. Under these conditions, we could imagine that we have only to observe the eye movements, count the saccades with their spatial coordinates and we would then obtain a first order statistical description of a picture. We could then observe and compute the successive displacements of the eye, looking for the predecessor or the successor of all fixations. We could thus make second, third and nth order statistics. In this way, we could treat the informative content of the picture in a manner very similar to Shannon's. Now the measurement of information content also measures the amount of complexity, because information in a Shannonian sense and complexity are closely linked.

Unfortunately, the problem is not so simple. We know, at least since the work of Buswell (1935), that eye movements are not random and cannot be random because a certain quantity of redundancy is necessary for perception (Molnar, 1974). But eye movements are not completely determined either. The eye doesn't explore the same picture in exactly the same way twice. This is quite natural. The exploratory pattern depends on both the stimulus and the subject. Not one of the models proposed to explain scanning strategy can ignore that subjective psychological forces intervene strongly in the exploration and that these subjective forces are in constant motion, in constant evolution. In the model proposed by Hochberg (1970), "cognitive exploration" principally obeys these subjective psychological forces while the "peripheral exploration" depends chiefly on the physical forces of the stimulus connected to the receiving physiological system. It is possible, to some extent, to foresee the structures of the peripheral exploration but those of the cognitive exploration are unpredictable. A certain amount of controversy surrounds this question. Noton and Stark (1971, a,b) affirm that subjects always explore the same picture with almost identical eye fixations even within several intervals, but the same picture will be explored by two subjects in a different way. Mackworth and Morandi (1967) think that all subjects gaze at the more informative part of the picture, that is to say, that different subjects' eye movements are somehow similar, while Gibson (1950) claims that eye movements are more or less unpredictable.

As far as individual differences in the exploration are concerned, the authors agree quite well. It is generally accepted that there are "enormous" individual differences. But it is hazardous to consider the very first fixation. The first two or three fixations, in the experimental conditions of Buswell, seem to be really random. Rather, we recorded the first 10 eye movements of 10 subjects looking at Manet's "Olympia" (Fig. 3).

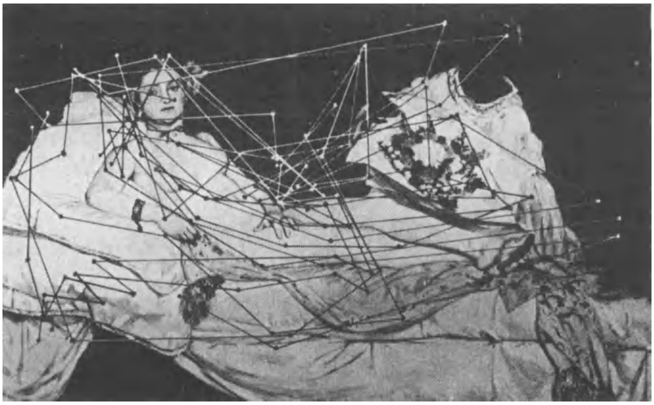

Figure 3
Graph of the first 10 eye movements of 10 subjects looking at Manet's "Olympia"

We can say, looking at figure 3, that the individual differences are not as "enormous" as it was generally supposed. We can find many sequences of 3,4 and sometimes 5 fixations which are nearly identical for several subjects. In any case, there is much more agreement between different fixations made by different people than we can expect by pure chance. We will therefore never know for certain if two neighboring fixations correspond to one or two targets, but we can estimate this probability. Under such conditions, if we compute statistics on identical sequences of fixations by confounding the fixation points within a circle with a visual radius of 1°, we can sometimes find quite good interindividual agreement. This permits the development of statistics on the frequency of fixations. Even more importantly, after sufficiently long observation, we can compute statistics on the succession of fixations. All these statistics can be easily transformed into probability. If we are not able to predict with precision the individual fixations hopefully we can determine the probability that a given target will be fixed upon. Furthermore, these statistics help us to estimate all the parameters necessary for the calculation of Shannonian information contained in the image, and to measure its complexity by using the method proposed by information theory. The measurement obtained in this way may be considered the expression of both objective and subjective complexity.

Graph theory and visual exploration

In a way closely related to eye movements, we tried to show (Molnar, 1974) that there are some relationships between eye movements and certain stylistic aspects of the picture. The classical works of art of the Renaissance, for instance, are explored by large and slow eye movements, while Baroque paintings, much more dense, much more animated, involve small and quick eye movements. The same phenomenon can be observed if we compare a subject's eye movements while looking at a picture by Vasarely with his eye movements while looking at a painting by Mondrian. The Vasarely will be explored much more quickly. This finding expressed in terms of information theory leads us to study eye movements by graph.

Of course, graphically, two points representing two possible targets are connected by a line if the eye goes from one to the other. In this way, it is possible to establish the graph of the exploration of a picture by joining with a line all points which are visually connected. We cannot survey or even enumerate all the positive aspects of the introduction of graph-theory in the field of visual aesthetics; we would only like to examine one, which seems to us to be the most important.

The associated matrix of a graph representing a sequence of eye movements is a stochastic matrix. We can, in addition, formulate the hypothesis that exploration by eye is Markovian, that is to say, that all individual fixations depend only on the preceding one. This hypothesis is strong especially when we consider the semantically guided exploration. But at the very beginning of the exploration, say during the first 5 or 6 fixations (the period called by Berlyne (1971) diversive and by us the "third type of exploration") we can reasonably admit the Markovian restriction (Molnar, 1981). So we can admit, at least as a hypothesis, that the pattern of eye movements during diversive exploration is stochastic and Markovian, as we have suggested several times since 1966.

Some of Markov's processes have a particular property, very important in communication theory, which we hope will be profitable for scientific aesthetics. This particular property is "ergodicity". In an ergodic process, every sequence produced by the process is the same as far as the statistical property is concerned. So, the ergodic property means statistical homegeneity. Still more important is the fact that all ergodic processes have a final equilibrium; that is, such a system in a shorter or longer time, after several transition states, reaches a final state where it will stay "ad infinitum". From our specific point of view, this signifies that, if the visual exploration of a picture is ergodic the eyes of the spectator begin to move over the picture in a random way, guided by different forces. However, after a variable period of time, the gaze settles on a determined average path and continues to follow this path (with some deviation) during the entire time it is viewing the picture.

If we admit that the exploration of a picture is Markovian, we can assert that a good composition must be ergodic. Indeed, besides the ergodic modality a Markovian process may be either decomposable (reducible), or periodic. The decomposable modality signifies, from our perspective, that the exploration will be limited to a single part of the picture. In the case of the periodic modality, the spectator's eye will oscillate between two distinct elements of a picture: as soon as the gaze rests on the first element, it is immediately attracted to the other one. Obviously, both modalities reflect bad compositions. The only structure for a good composition is the ergodic one. Knowing the transition-probability matrix, it is possible to calculate the form of the final equilibrium and the number of steps necessary to reach it. These two data should be considered as characteristic of the quality of a pictural composition. Naturally, we tried several times to demonstrate experimentally the validity of these propositions. Unfortunately, it is extremely difficult and also very expensive to carry out experimentation in this field.

We could not hope to establish second-order statistics on all individual eye movement. We could not count the predecessors of every fixation point. That would have been a very difficult task, and, in addition, probably useless. Because of the inaccuracy of the eye, all fixations are not necessarily meaningful. To simplify our task and to reduce the difficulty, we treated a certain number of fixations together. We determined, by means of first-order statistics obtained by the recording of a very large number of eye movements, the density of distribution of the fixations on the picture. We next chose a few, say 6 or 8, areas which received the most fixations. Then we counted the successive displacements from one area to another. The frequency of these displacements was transformed into probability. Figure 6 shows the partition of one of the favorite stimuli of our Laboratory, Manet's "Olympia".

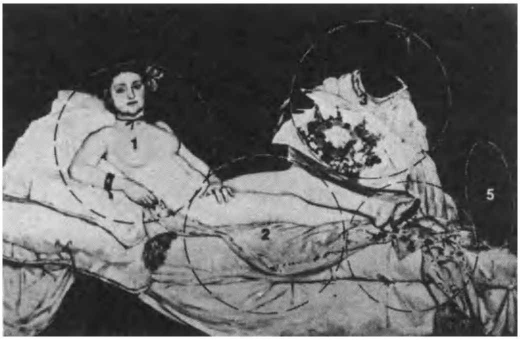

Figure 4
Schema of a partition of Manet's "Olympia" in 5 areas
(the 6th area is the complement, the rest of the picture)

The matrix of transition probability, established after more than 3.000 fixations, is as follows :

	1	2	3	4	5	6
1	.3	.3	.2	0	0	.2
2	.2	.3	.2	.1	0	.2
3	.1	.2	.1	.3	.1	.2
4	.1	0	.2	.3	.1	.3
5	0	.2	.1	.1	0	.4
6	.2	.2	.1	.1	0	.4

This matrix signifies that, if the eye is directed to Area 1, the probability that the next fixation will be in Area 2 is .3, in Area 3 is .2, etc. It is important to notice that this average stochastic structure of the picture is nearly identical to the structure obtained after the exploration of the individual subject. Hence, in contrast to detailed fixation-by-fixation treatment of exploration, there are no differences between subjects in the statistical structure of visual exploration. The exploration of "Olympia", whose matrix of transition probability is reproduced, reaches this final equilibrium in a very short time. After less than 25 iterations, a stable state is obtained that can be expressed by the following vector.

$$\begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \\ (0.181, & 0.211, & 0.153, & 0.140, & 0.036, & 0.276) \end{array}$$

We can see that the most explored area is, and remains henceforth, Area 2.[*] Twenty-one percent of the fixations occur in this region. The next is Area 1, around the head of "Olympia", followed by Areas 3, 4, and 5. N° 5 designates the part, little explored, corresponding to the cat, that we have included for semantic reasons only. Although these results are promising from a theoretical view-point, they are insufficient from a practical way, as the fixations tend to cluster on meaningful regions of the picture. But, as it was said earlier, the meaningful regions coincide with the sensorally important regions as those of luminance or of changing contrast, and so on. The six regions are obviously too vast for a precise study of the scanpaths.

We established the transition matrix for a picture less prestigious than Manet's. In the picture by one of us (D. Ratsikas, fig. 5a), we joined the fixation points in 1296 zones for ten subjects and established the transition matrix of probability. The scanpaths of 4 subjects are shown on figure 5b. From this matrix, we simulated the exploration on computer and obtained the final balance after 28 iterations. The shape of this final balance is shown on figure 5c.

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[*] Area 6 is the surface remaining, not encompassed by the five more explored Areas.

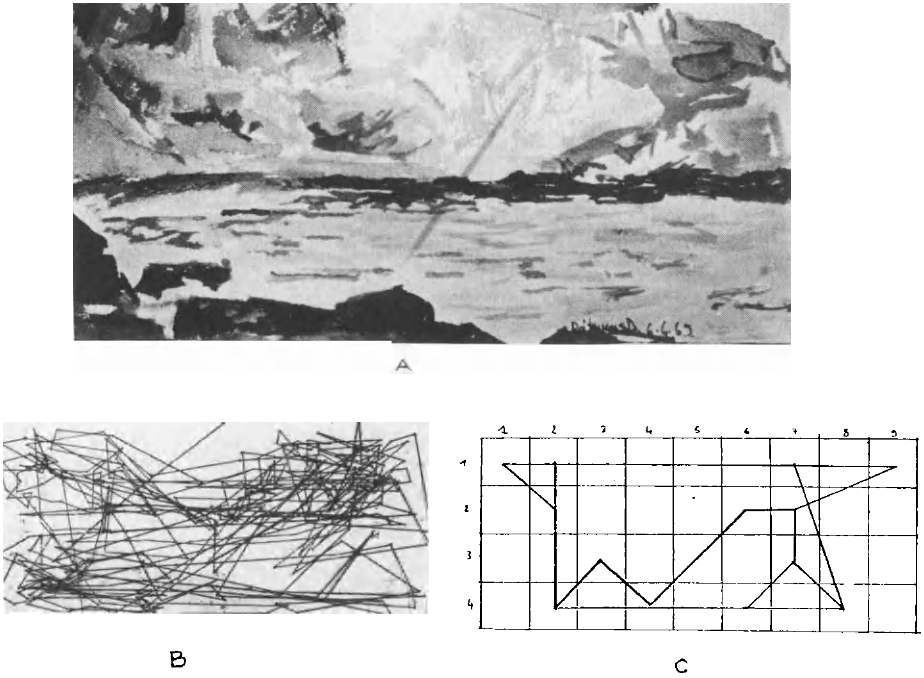

Figure 5
a : Landscape. D. Ratsikas (Water color); b : Scanpath of 4 subjects;
c : Final equilibrium.

CONCLUSION

The few points which have just been quickly pointed out don't pretend to treat the vast image processing on an aesthetical view-point, if we can talk about processing in this case. We only hope that we succeeded in showing that this field, neglected by scientists, is a privileged field for very promising investigations.

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SIMULATION MODEL OF JUDGEMENTS OF ASYMMETRY OF A TRIANGLE BASED ON EYE FIXATIONS

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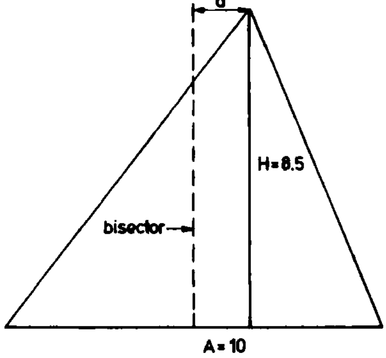
EXPERIMENT

Procedure: Discrimination between an isosceles and a scalene triangle, by the use of a forced choice technique is considered. Triangles were exposed successively and the time of each exposition was not limited. It was stopped after a subject gave an answer. During some trials positions of a subject's eye were recorded.

Material: All the triangles used in the experiment had a horizontally oriented base. Each triangle was constructed by using both a base and a height of a constant length. There were used 38 scalene triangles and one isosceles triangle. Scalene triangles had the upper apex shifted to the left side or to the right side from the bisector of the base (see Fig.1). The distance "d" between triangle height and the bisector was used as a measure of triangle asymmetry. In the experiment asymmetries varied within the range between 1.9 to the left side and 1.9 to the right side, with step equal to 0.1. Each of the scalene triangles was shown to a subject 4 times and the isosceles triangle was shown 8 times. The triangles were exposed at random. One series contained 160 expositions.

Fig.1



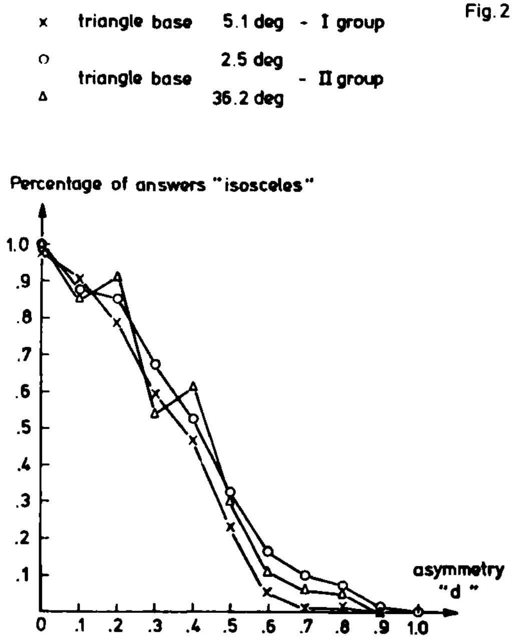
Subjects: Two groups of undergraduate students with normal vision served as subjects in the experiment. The first group consisted of 12 subjects who discriminated triangles of a base size equal to 5.1 deg. The second group consisted of 10 subjects and they discriminated triangles of a base size equal to: (i) 2.5 deg and (ii) 36.2 deg.

Results: Distributions of answers, averaged between left and right asymmetries are shown in Fig.2. It is apparent from the Figure, that performance of triangle discrimination was equally good for both groups of subjects and for all triangle sizes used in the experiment. Thus, shape of triangle was perceived by subjects invariantly, regardless of the triangle size.

The distribution of eye fixations, observed for subjects from the first group during triangle discrimination, was analysed. It appeared to be nearly a two-dimensional Gaussian distribution with mean abscissa of fixations near the bisector of the triangle base and mean ordinate of fixations equal to 0.47·H above the base.

A comparison between experimental results and predictions made by the simulation model is presented in Figs. 3 – 5.

Fig. 2

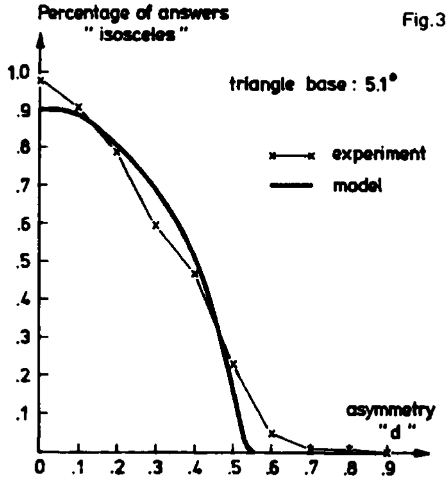


SIMULATION MODEL

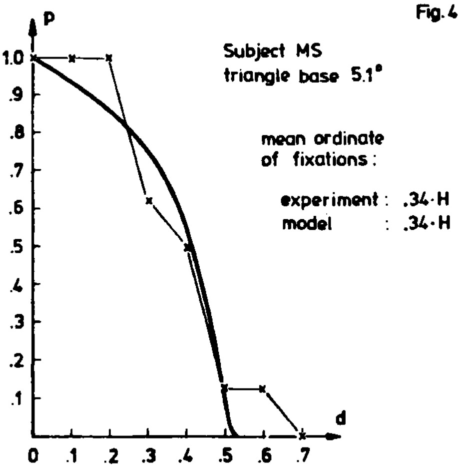
Basic assumptions :

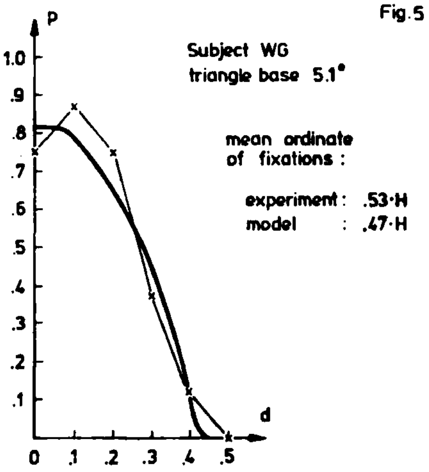
1. Triangle discrimination is based on the identification of triangle asymmetry "d".
2. The identification is performed during the fixation of the eye near the centre-of-gravity of triangle apexes weighted by the cortical magnification factor (CMF) of area 17 of visual cortex.
3. The place of cognitive fixation along the direction parallel to a triangle base is random and it is subject to a Gaussian distribution of fixation density during fixeting the midway point of a segment.
4. The place of cognitive fixation along the direction perpendicular to a triangle base is subject to interpersonal variability.
5. Performance of discrimination is limited by an error margin of the position estimation of triangle apexes which follows the relation between the inverse of CMF and the distance from fixation on the screen (R). Within a ring of the screen roughly between 1.5 deg and 25 deg of eccentricity the inverse of CMF is directly proportional to R.

Using a procedure of best fitting between theoretical and experimental answer distributions, the mean ordinate of fixations was estimated.



The mean ordinate, estimated by the model for the first group of subjects is equal to 0.44·H, which is in good agreement with the experimental value, namely 0.47·H (Fig.3). Similarly, there was found a close correspondence between measured and estimated ordinates of fixations for individual subjects (Figs. 4 and 5).





For a given subject, the theoretical distribution does not depend on a triangle size provided the mean eye position is constant. This is because of the linear part of the relation between inverse of CMF and R. Note, that outlines of triangles used in the experiment fell within the considered ring of a screen, where the relation is linear.

CONCLUSIONS

1. On the basis of several assumptions related to the organization of area 17 of visual cortex and oculomotor activity as well as strategy of recognition, it is possible to predict the subject's performance during triangle discrimination.
2. Constancy of shape perception under size variation of a figure results from linearity of the relation between inverse of CMF and R.
3. Individual differences in triangle discrimination might result from differences in the mean ordinate of subject's eye fixation.

Characteristics of Fixations in Human Infants: Durations

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INTRODUCTION

It is widely believed that visual processing occurs during fixations and that a saccade is initiated to the next stimulus element once "processing" of the current stimulus element is completed. Thus, free-viewing has been regarded as a deliberate, centrally controlled, sequential scan of the visual scene. We challenge this with evidence that the event which triggers a saccade is essentially random in time and independent of the current fixation.

METHOD

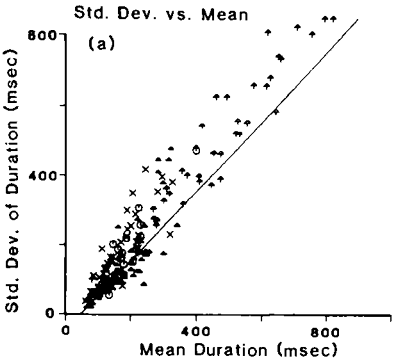
Eye movements were recorded using a TV based infrared corneal reflection system (Applied Science, Model 1994) with a resolution of about 0.5 degrees and a sample rate of 60 Hz (1). Subjects were 243 infants (14-256 days) and 11 naive, unpracticed and uninstructed adults. Subjects viewed rear-projected static stimuli or a small (1 deg by 1 deg) spot that was moved from place to place under the control of an experimenter every few seconds to keep the infant's attention. The static stimuli consisted either of simple black and white forms from 5 to 30 deg in size, texture gradients of lines or checks, or complex realistic scenes in color.

RESULTS

There are strong subject and stimulus effects on fixation duration. On average, infants made more saccades than adults: about 4/sec vs. 2/sec for the complex scenes, and about 2/sec for the spot (adults would fixate until the spot was moved by the operator). Thus, the small spot evoked longer fixations than the larger more complex scenes.

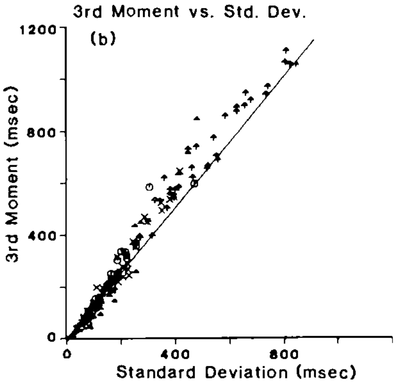
The distribution of fixation durations is similar for all subjects (unimodal and positively skewed) as shown by the linear relationship between their moments (Fig.1) (root moments are shown and are corrected for bias and grouping). The relationships among the moments of most distributions are either not linear or, if linear, have slopes less than those observed. The exponential distribution provides a reasonable approximation as shown by the solid lines.

The exponential distribution is usually associated with a simple memoryless mechanism - it describes the probability of the waiting time to a first event when the events are occurring randomly in time (2).



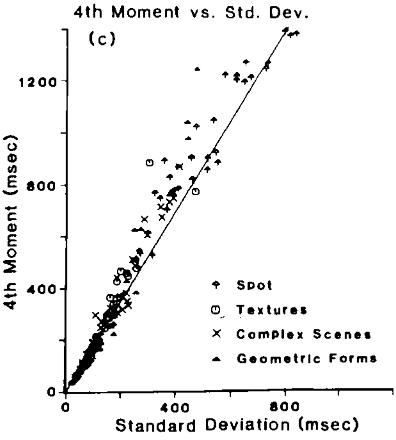
Std. Dev. vs. Mean

(a)



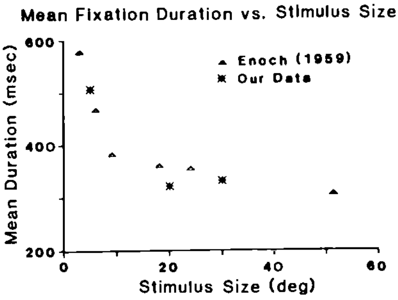
3rd Moment vs. Std. Dev.

(b)



4th Moment vs. Std. Dev.

(c)



This mechanism is appropriate to our situation and suggests that fixations are terminated by saccades which occur randomly in time.

Actually, the observed moments are slightly hyper-exponential, having more dispersion than the true exponential. This is probably due to variations in the mean probability rate of saccade occurrence from fixation to fixation. Such variation gives rise to a compound exponential distribution; the Pareto distribution fits the observed moments quite well. However, an individual fixation is still terminated randomly.

The non-zero intercept in Fig. 1a indicates that there is a period during every fixation in which a saccade does not occur. This minimum period is about 50 msecs for the infant and 100 msecs for the adult. It probably represents saccade preparation time, although other processes may be involved in determining this period.

The randomness of fixation termination is hardly the hallmark of central processing and might indicate that termination is under the control of a mechanism other than the fixation process per se. A possibility is that fixations are terminated by a visual event occurring (randomly) in the visual field outside of the foveal region (cf. the saccadic reflex). Fixation duration would then depend on the likelihood of such peripheral events occurring. As the area of the stimulated peripheral retina increases, the chance of a triggering event occuring should increase and so, on average, should reduce the duration of fixations. We have confirmed this prediction with adults (Fig.2). Our results are in good agreement with Enoch's (3).

When adults view larger stimuli, the average amplitude of their saccades and the breadth of their scans also increases. This suggests that the saccades which terminate the fixations are visually triggered, and that peripheral visual stimulation is responsible for fixation duration. Infants' mean durations are less affected by stimulus sizes from 5 to 30 deg, but are markedly increased for the one deg. spot.

CONCLUSIONS

1) Fixations are terminated by saccades which occur RANDOMLY in time as shown by the exponential distribution of fixation durations.

2) There is a minimum time during a fixation in which a saccade does not occur. This is about 50 msec for infants and 100 msec for adults. This minimum period may represent saccade preparation time.

3) Mean fixation duration for infants is much shorter than that for adults.

4) Mean fixation duration is strongly dependent on stimulus size. For larger stimuli, saccades have greater amplitude and occur more frequently. This supports the argument that fixations are terminated by peripheral stimulation not by central processing.

5) We postulate that, at least under free-viewing or minimal task conditions, visual processing occurs asynchronously with eye movements and/or visual processing is over before the fixation ends. The time spent fixating after about 100 msecs is a waiting time for the triggering of a saccade by peripheral targets.

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OCULAR SACCADE LATENCY AND COGNITIVE PROCESSING IN A FACE RECOGNITION TASK IN INFANCY

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INTRODUCTION

A TECHNIQUE IS DEVELOPED IN ORDER TO COMPARE PERFORMANCES OF THE TWO CEREBRAL HEMISPHERES IN A FACE RECOGNITION TASK IN 4 TO 9 MONTH OLD INFANTS.

AS IN ADULT EXPERIMENTAL STUDIES, THE SELECTIVE STIMULATION OF EACH HEMISPHERE IS MONITORED BY VERY BRIEF VISUAL STIMULATION IN ONE VISUAL HEMIFIELD AT A TIME.

DIFFERENTLY FROM ADULT STUDIES, THE DEPENDENT VARIABLE RECORDED HERE IS THE LATENCY OF THE OCULAR SACCADE IN RESPONSE TO THE ONSET OF THE STIMULUS.

METHOD

STIMULI :

COLOUR SLIDES OF FEMALE FACES. FRONTAL VIEW. NEUTRAL EXPRESSION

TWO DIFFERENT FACES ARE PRESENTED: THE FACE OF EACH INFANT'S MOTHER AND A STRANGER'S FACE THAT WAS DIFFERENT FOR EACH SUBJECT.

CLUES OTHER THAN CONTOUR AND INTERNAL FEATURES ARE ELIMINATED.

FACES OF MOTHER AND STRANGER HAVE CLOSE PHYSICAL CHARACTERISTICS (LUMINANCE, COLOUR, CONTOUR).

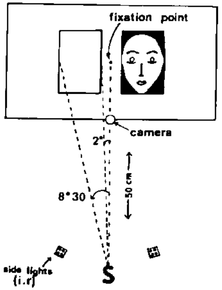
PROCEDURE :

MOTHER AND STRANGER STIMULI ARE PRESENTED IN RANDOM ORDER, ALTERNATELY IN THE RIGHT VISUAL FIELD AND THE LEFT VISUAL FIELD.

STIMULI ARE PROJECTED AT 2° (VISUAL ANGLE) FROM A CENTRAL FIXATION POINT.

EACH SUBJECT RECEIVES 40 STIMULI: 20 IN EACH VISUAL FIELD (10 MOTHER AND 10 STRANGER PER VISUAL FIELD).

STIMULI ARE PRESENTED FOR 350 MS FOR 4 TO 6-MONTH OLDS, AND FOR 250 MS FOR 7 TO 9-MONTH OLDS.



STIMULUS DELIVERY OCCURS WHEN AND ONLY WHEN S. FIXATES THE CENTRAL POINT. S.'s FIXATION IS ASSESSED BY CORNEAL REFLEXIONS OF THE CENTRAL POINT AND OF LATERAL I.R SOURCES.

RESPONSES :

LATENCY OF THE OCULAR SACCADE - FROM THE ONSET OF THE STIMULUS - IS MEASURED ON VIDEO RECORDINGS. THE ONSET OF A SACCADE IS ATTESTED BY A SHIFT OF THE I.R CORNEAL REFLEXIONS.

SUBJECTS :

40 MALES (19 AGED 4 TO 6 MONTHS, 21 AGED 7 TO 9 MONTHS).

RESULTS

THE TRIALS ARE DIVIDED INTO TWO SUCCESSIVE IDENTICAL PHASES (PHASE 1 AND PHASE 2) TO DISTINGUISH BETWEEN ANY MODIFICATION OF THE RESPONSES DURING THE EXPERIMENT.

ANOVA (2 PHASES x 2 VISUAL FIELDS x 2 FACES) SHOWS THAT :

OCULAR SACCADE LATENCIES SIGNIFICANTLY DECREASE FROM PHASE 1 (P_1) TO PHASE 2 (P2), ($p < .001$).

S. RESPOND FASTER TO MOTHER THAN TO STRANGER STIMULI ($p < .005$).

LATENCIES SIGNIFICANTLY DECREASE FROM P1 TO P2 FOR MOTHER STIMULI, NOT FOR STRANGER STIMULI.

THE DECREASE OF LATENCIES FROM P_1 TO P2 FOR MOTHER STIMULI IS GREATER IN THE LEFT VISUAL FIELD (LVF) THAN IN THE RIGHT VISUAL FIELD (RVF).

IN PHASE 2 :

1) LATENCIES ARE SHORTER FOR MOTHER STIMULI. THIS EFFECT IS STRONGER IN THE LVF THAN IN THE RVF (Faces, $p < .001$; VF, $p < .025$; Faces for LVF, $p < .001$; Faces for RVF, $p < .05$).

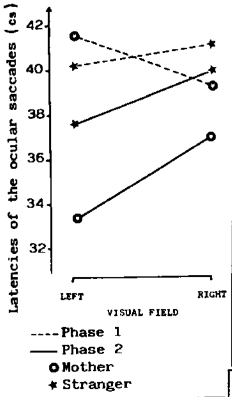
2) S. RESPOND FASTER IN THE LVF THAN IN THE RVF FOR MOTHER - NOT FOR STRANGER - STIMULI (VF for Mother, $p < .005$; VF for Stranger, $p > .10$).

IN PHASE 1 :

DIFFERENTIAL RESPONSES ARE ALREADY PRESENT AS SHOWN BY SIGNIFICANT INTERACTION BETWEEN VF AND FACES ($p < .05$).

AGE : 4 TO 6 MONTH OLDS DO NOT DIFFER FROM 7 TO 9 MONTH OLDS.

DISCRIMINATION BETWEEN MOTHER AND STRANGER STIMULI (WHICH IMPLIES RECOGNITION OF THE MOTHER'S FACE) IS ATTESTED BY SHORTER LATENCIES OF OCULAR SACCADES IN RESPONSE TO MOTHER STIMULI.



ARE THE SHORTEST LATENCIES EXCLUSIVELY RELATED TO THE RECOGNITION OF THE MOTHER'S FACE ?

NO, SINCE IN ANOTHER EXPERIMENT (de SCHONEN, GIL de DIAZ and MATHIVET 1986) UNKNOWN FEMALE FACES WERE USED, ONE OF WHICH WAS FAMILIARIZED DURING THE EXPERIMENT; 4 TO 11 MO. OLDS ALSO RESPONDED FASTER TO THE FAMILIARIZED FACE (AFTER A FEW TRIALS OF FAMILIARIZATION) THAN TO THE NON FAMILIARIZED FACES.

ARE THE SHORTEST LATENCIES EXCLUSIVELY RELATED TO THE MORE FAMILIAR STIMULUS ?

NO, SINCE IN A REPLICATION OF THE de SCHONEN et al. (1986) EXPERIMENT WHERE FACES WERE REPLACED BY SIMPLE GEOMETRIC SHAPES, S. RESPONDED FASTER TO THE NON FAMILIARIZED SHAPES THAN TO THE FAMILIARIZED SHAPE.

THUS THE RELEASE OF THE OCULAR SACCADE IN 4 TO 11 MO. OLDS SEEMS TO BE UNDER THE CONTROL OF COGNITIVE DECISIONS.

THERE IS AN ASYMMETRY BETWEEN THE TWO VISUAL FIELDS: FASTER RESPONDING IN THE LEFT VISUAL FIELD - RIGHT HEMISPHERE (LVF-RH) THAN IN THE RIGHT VISUAL FIELD - LEFT HEMISPHERE (RVF-LH).

CONCLUSION

. INFANTS (AS YOUNG AS 4-MONTHS) CAN EFFICIENTLY PROCESS VISUAL INFORMATION DURING A DELAY OF PRESENTATION AS SHORT AS 350 MS.

. WITHIN THIS DELAY THEY CAN RECOGNIZE THEIR MOTHER'S FACE ON THE BASIS OF FACIAL FEATURES.

. OCULAR SACCADE LATENCY CAN BE RELATED TO INFORMATION PROCESSING IN THIS TYPE OF TASK.

. THERE IS AN ASYMMETRY IN THE REACTIONS OF THE TWO HEMISPHERES TO FACES. THE DIRECTION OF THE ASYMMETRY IS SIMILAR TO THAT FOUND IN MOST ADULT STUDIES: RIGHT HEMISPHERE ADVANTAGE IN FACE PROCESSING.

REFERENCE :

de Schonen S., Gil de Diaz M., Mathivet E. (1986)
Hemispheric Asymmetry in Face Processing in Infancy
In H.D. Ellis, M.A. Jeeves, F. Newcombe & A.W. Young (Eds.)
Aspects of Face Processing (NATO ISI SERIES), Dordrecht: Nijhoff

STUDY OF THE MODALITIES OF VISUAL EXPLORATION IN YOUNG CHILDREN

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INTRODUCTION AND AIM OF THE RESEARCH

In reading or during a related task, visual exploration is carried out by young children through a lateral displacement of the head combined with ocular movements.

The aim of this research is to study the modalities of oculo cephalic coordination depending upon :

. the age of the child
. the nature and spatial arrangement of the task

Is it possible to show that modalities of oculo cephalic coordination are specifically related to either of these variables ?

HYPOTHESES

1° Variations of age, nature of the task and spatial arrangement modify modalities of oculo cephalic coordination observed.

2° Modalities of oculo cephalic coordination are dependent on distance between graphic elements.

EXPERIMENTAL PROCEDURE

1° Age : 5, 6, 8, 10 years old.

2° Nature of the tasks

. Visual discrimination of drawings (5, 6, 8, 10 years old)
. Deciphering of pictograms (5, 6, 8, 10 years old)
. Reading of alphabetic text (8 and 10 only)

(every task involves visual exploration oriented from left to right with return sweeps from right to left).

3° Spatial arrangement in every task

. Closely spaced (5 mm separation between graphic elements)
. Widely spaced (20 mm separation)

Nature of the task and spatial arrangement are crossed.

RESULTS

1° Different morphologies in the movement are observed :

. Ocular ⟶ Saccades (1 line :  ; saccade ⩾ 1°) or Micro saccades (1 line :  ; micro saccade < 1°)

. Cephalic ⟶ Linear cephalic movement (1 line : ) or Non Linear cephalic movement (1 line : )

2° Typical modalities of coordination specifically related to the age of the child and to the nature and spatial arrangement of the task ;

. Ocular saccades combined with linear cephalic movement (fig. 1) are observed specifically at the age of 5, and at the age of 8 in the reading of text ;

. Ocular micro saccades combined with linear cephalic movement (fig. 2) are observed specifically at the age of 10.

Fig. 1 (1 line)

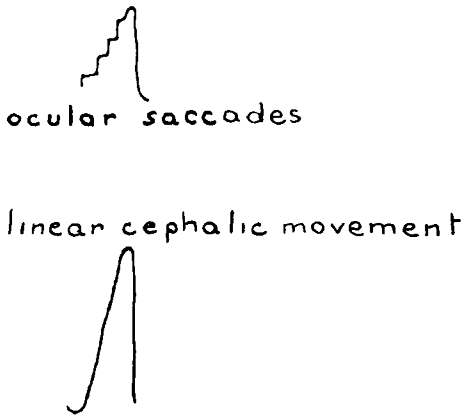
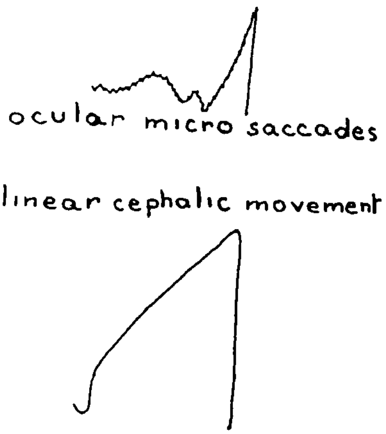


Fig. 2 (1 line)



CONCLUSION

1° Modalities of oculo cephalic coordination vary with age only. One must note that these variations are related to the distinction pre readers and beginners vs. readers. So, the first hypothesis is partially confirmed. Further more there are important individual differences.

2° Modalities of oculo cephalic coordination are not dependent on distance between elements. So, the second hypothesis seems not confirmed. Further-more there is diversity of materials, composed by graphic elements, used in every class (pre school and primary school) which prepare children to adjust their capacities of perceptual analysis to different situations proposed.

DIFFERENTIAL STUDY OF EYE MOVEMENTS

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INTRODUCTION. In general, when we adjust our body -or a rod- to the upright position we bring into play a double system of references: visual and postural. In the Rod and Frame Test, the subject is required to place a rod in an upright position although the only visual references available are those of a tilted tunnel/frame; most deviations of the rod from the upright are made in the same direction as the tilt of the frame.

Under these experimental conditions there are marked interindividual differences. We have suggested (Ohlmann,1985) that differences in the impact of peripheral visual references are due to the triple vicarious system responsible for balance and orientation (vestibular, haptic and visual). Spatial references of field dependents may be more strongly based on the visual modality, those of field independents on vestibular information. Consequently it should be possible to find some links between eye-movements and the way the subject resolves the visual/postural conflict.

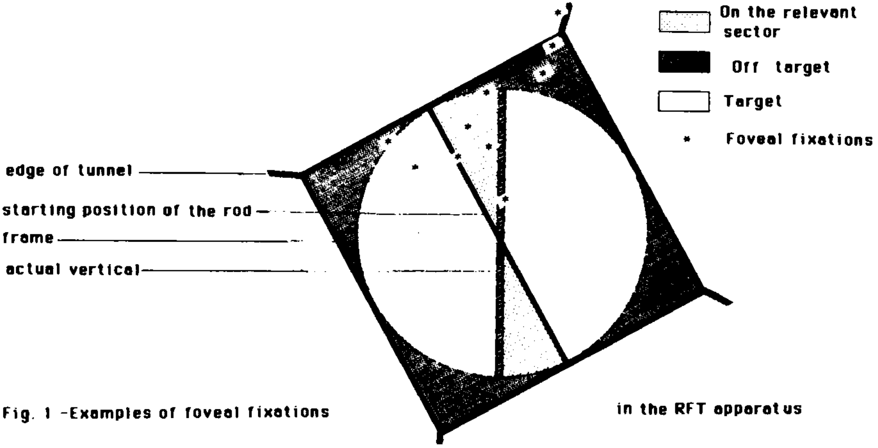

Fig. 1 -Examples of foveal fixations in the RFT apparatus

HYPOTHESIS. 1) independents and dependents should differ in the location of foveal fixations. The most "relevant sector" ie the area encompassed between initial position of the rod and actual vertical (see fig. 1) should be more often fixated by independents than by dependents. 2) Where do the field dependents look? two possibilities: a) it is the peripheral visual field that contains most relevant information for them. They refer to it by fixating the frame and the points beyond (the sides of the tunnel) b) they perceive the tunnel by means of peripheral vision. As they are accustomed to directing themselves by use of this means, they do not need to fixate the frame as such but rather the centre of the target so as to gather a maximum of information about the peripheral field.

METHOD. Observers: 22 girls aged 11 to 12 (more dependent than boys and than older females). Apparatus: Oltman's portable Rod and Frame Test: 4 trials without recording eye-movements and 4 with Nac 4 Eye Recorder. Subjects are classified independent or dependent according to their position above or below the median of distribution. Dependent variables (see table I and figure 1): collected in the following manner: for each subject 3000 images are obtained . We choose to take fixation co-ordinates every two seconds.

RESULTS. For the population studied and for this apparatus, hypotheses 1 and 2a are confirmed. Independent and dependent girls do not look at the same zone with the

same frequency(see table I and figure 2, V1 to V6) and, as shown by most research (Rozestraten 1981), they do not differ in number of fixations (V7) or distance from the centre of the target (V8).

TABLE I. comparison between 9 Independents(IC) and 10 Dependents (DC). _A:_ frequency of fixations; _B:_ number of fixations; _C:_ distance of fixations (cm); _D:_ angles (degree).

Variables	*mean* *IC*	*mean* *DC*	p^*
A. frequency of fixations			
V1: frame and beyond	0,016	0,10	<0,007
V2: on the target	0,97	0,87	<0,004
V3: on the relevant sector	0,82	0,62	<0,006
V4: on the rod	0,67	0,44	<0,01
V5: on the vertical	0,08	0,07	0,16
V6: centre of the target	0,14	0,08	>0,10
B. number of fixations			
V7: during 4 trials	46,9	52,9	>0,10
C.distance of fixations(cm)			
V8:from the centre	5,11	5,63	>0,10
D. angles(degree)			
V9: rod/fixation	7,2	14,2	<0,01
V10: vertical/fixation	10,1	15,2	<0,04

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*variables A: Mann -Whitney *U* test; variables B,C,D: Student *t* test

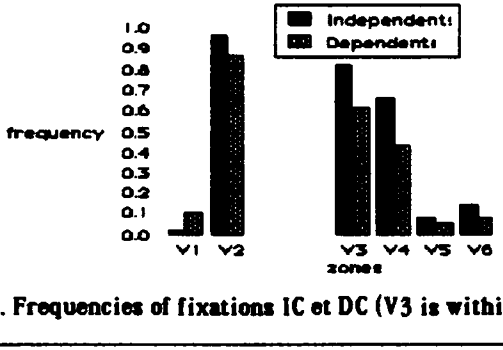

Fig. 2. Frequencies of fixations IC et DC (V3 is within V2; V4 and V5 are within V3)

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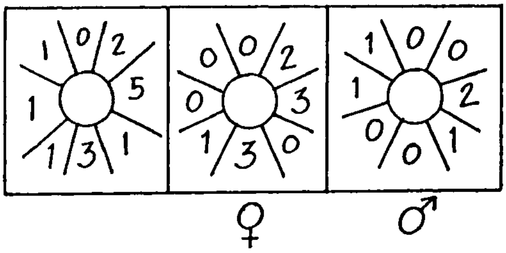
This research was designed to assess eye movement in response to requests to "see," "hear", "feel"... (inside your head)

- All Ss had 1 preferred sector on the first move, and 1 to 3 preferred sectors across the first four moves:

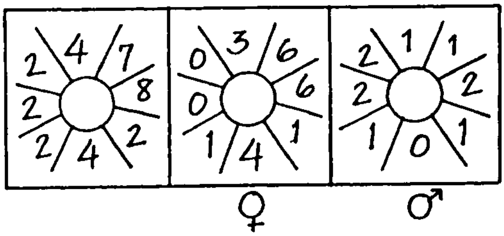
  2 Ss $P \leq .05$
  12 Ss $P \leq .001$

- Nine Ss had 5% to 73% of eye movement time in defocused gaze within the 1° radius "uncounted space"

Sectors preferred on first movement for all Ss

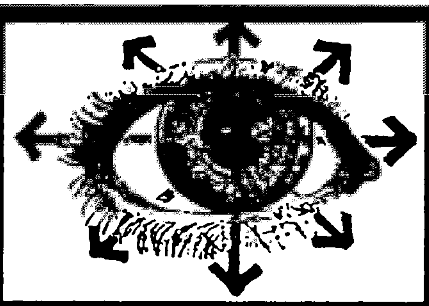


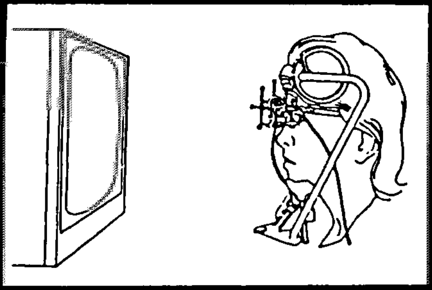
Sectors preferred across the first four movements for all Ss



This data adds to the mounting evidence that cognitive processes drive eye movements.

NON-ATTENDING* EYE MOVEMENTS ASSOCIATED WITH COGNITIVE PROCESSING





<u>SUBJECTS:</u> 14: 9♀+5♂ · 19-50 yrs.

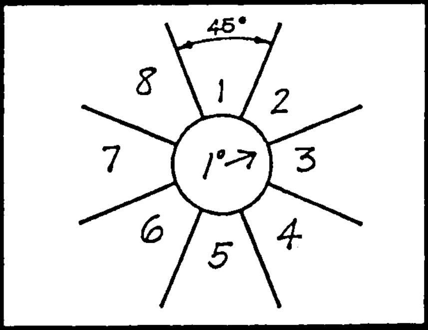
<u>STIMULUS:</u> 30 sensory based commands, given by voice

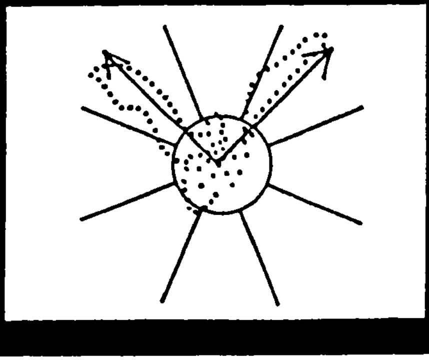
<u>EXAMPLES:</u>

- See green moss on a stone
- Hear a telephone ring
- Feel a warm shower

<u>TESTING SITUATION:</u>

- ★ Subject seated, with head movements restricted, facing a blank 17" TV screen.
- ★ Subject fitted with Biosystems Eyetrack monitor, Model 200-1 ambient low light, low noise





<u>SAMPLING CRITERIA:</u>

- <u>DATA COLLECTION</u>-
  - ★ 5 sec. of eye movement data collected on each of 30 stimuli for a total of 150 sec.
- <u>INTERFIXATION DISTANCE</u>-
  0 degrees to 25
- <u>FIXATION DURATION</u>
  100 ml sec.

* Non-Attending Eye Movements, heretofore called "random", not associated with "looking".

PUPIL CHANGES IN MEMORY TASKS

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The whole literature in pupillometry related to cognitive activity supports a model of Pupillary Response (P.R.) which has never been tested for itself.

Model underlying pupillometry:

1. Pupil dilation is an increasing function of cognitive load. It reflects second to second changes of cognitive load.

2. A baseline of pupil diameter exists which is relative to the absence of cognitive activity: after every cognitive task, pupil diameter returns to baseline.

3. The characteristic variable of pupillary response evoked by a cognitive task is dilation measured in reference to baseline.

4. The baseline is still likely to vary. P.R. is then supposed to be transferred by the same value as baseline, and dilation amplitude remains constant.

5. Pupillary responses evoked by a cognitive task are independent of the sensory modality involved in the detection of signal (auditive or visual).

Being interested in the field of ergonomics, we have chosen to test this model in the case of a continuous activity of long duration.

TEST RESULTS

Using the same memory tasks (recall of 4 or 7 digit string; transformation of a 4 digit string) with an acoustic presentation or a visual one, we have shown that:

1. P.R. are dependent on the **sensory modality** involved in the stimulus detection. For auditive modality, the peak of dilation becomes higher as processing load increases for this task. But visual modality does not show this relation between dilation peak and processing load, as if the visual input involves different causes of pupil changes.

2. During the period preceding the task, in which the subject is waiting for the first stimulus, pupil diameter is very variable and this variation is not distributed randomly about a mean value (non ergodic). Then P.R. **reproducibility** is low because the responses are measured in reference to mean diameter during the period preceding task.

3. Pupillary responses are affected by **habituation**. Pupil diameter and dilation amplitude tend to decrease during the experiment. The value of diameter are not more stable than the values of dilation and consequently are not more significant to represent P.R.

MODELIZATION OF P.R. AS A FUNCTION OF MEMORY LOAD.

Transfer function:

Second order visco-elastic system
Input function is the number of digits to recall (S.T.M. load)
Characteristic values: Time constant (C)
- Gain (G)
- Damping Factor (F)

The adjustment between P.R. and model output is performed by the Least Squares Method. Fig 1 presents the optimal adjustment of a P.R. (Intersubject mean for 7 digit span task with auditive modality) to model output with the indicated value of characteristic parameters. The Mean Square Error (E) is drawn near the Y-axis.

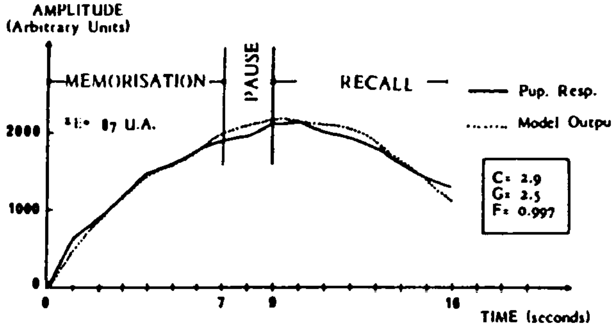
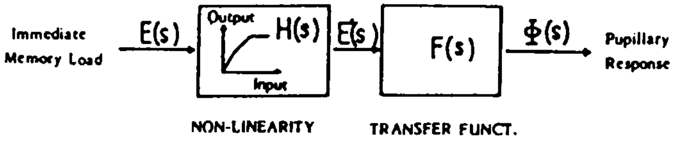


Fig 1 : OPTIMAL ADJUSTMENT BETWEEN A P.R. AND MODEL OUTPUT.

RESULTS

1. **Non-linearity** of pupillary system. The response of pupillary dilation is not a continuously increasing function of item number in memory.



The linear function used takes saturation into account by an interpolated filter H(s) on the input and then simulates non-linearity.

2. The transfer function's **characteristic parameters**, C, G, and F define P.R. more exactly than classical parameters like dilation peak, slope, mean value... They provide homogeneous criteria to compare P.R. of various durations.

3. The model is a **real-time model** of the memory load effect. It allows simulation of various changes of load during cognitive activity.

CONCLUSIONS

The model underlying pupillometry has not been verified for continuous cognitive activity in the visual modality. Thus the application of this method to study mental workload on visual displays is jeopardized.

But the transfer function we have developed allows various real-time changes of memory load to be simulated.

INFLUENCE OF LUMINANCE

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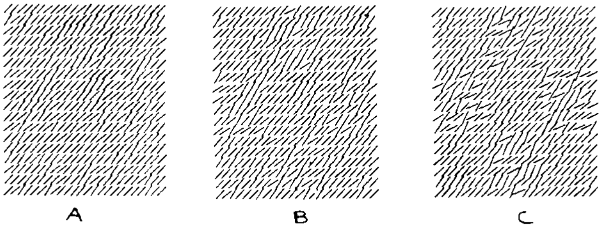
Psychologists willingly consider that Gibson was the first to introduce the study of visual texture into the research themes of psychology. But the importance of texture in sight has been explicitly pointed out by the cubists, as for the optical and perceptual effects of texture they have been studied by the bauhaus painters and, above all, by Moholy-Nagy. So texture always was an important feature of pictorial art.

Some examples of utilization of textures in visual art.

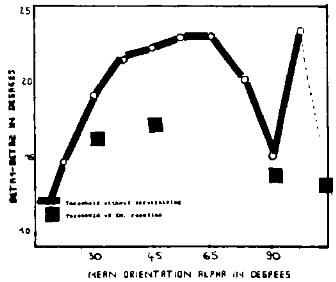
1



The total surface of the stimulus is divided into 9 equal squares composed of bars which have different slants. The inclination of the bars is defined by a constant α angle and a small amount randomly defined between 2 limits, β1- β2 which changes from one zone to another.

We recorded the eye movements on these stimuli. We notice the significant increase of the fixations from one zone to another (from a to b).

The threshold (black squares) is significantly lower to the one obtained in condition of exploration without scanning.



The threshold of segregation as a function of differences between β1- β2.

3

a	b	a
b	a	b
a	b	a

TAB.1

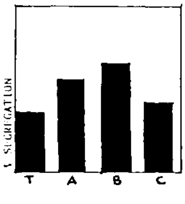


FIG.1

	TEST		A		B		C	
	a	b	a	b	a	b	a	b
Ist order statistic	ident.		ident.		ident.		ident.	
Luminance	ident.		.3	.6	.2	.6	ident.	
λ dom.	ident.		ident.		450	470	420	480
Purety	ident.		ident.		ident.		ident.	

TAB.2

A,B,C are 3 stimuli each constituted of 9 areas a or b (tab.1). Their organization is shown in tab. 2.

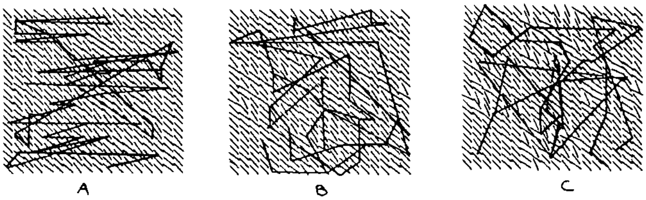
Results are shown in fig.1

Then we conclude that difference in wavelength and luminance is an important factor of texture segregation.

ON TEXTURE DISCRIMINATION

HYPOTHESIS 1
Eye movements are influenced by the difference of the visual texture of the surface. (See 1-2).
HYPOTHESIS 2
The mechanism of fixation is more sensitive to the difference of texture described in statistical terms than the cognitive system (strong hypothesis). (See 1).
HYPOTHESIS 3
The description of texture in terms of 1st and 2nd order statistics based on the frequency of the elements is not sufficient to explain the segregation of a surface built up by different textures.
Chromatic constituents described in colorimetrical terms (luminance and chroma) are important forces responsible for the spontaneous segregation of textures without scrutinizing (see 3).

2



TYPICAL SCANPATHS

.43	.31	.06	.06	.06	.06	0	0	0
.25	.38	.09	.06	.12	.03	0	.03	0
.07	.35	.5	0	.07	0	0	0	0
0	.18	0	.37	.25	.06	.06	0	.62
.02	.10	0	.12	.46	.08	.06	.10	.04
0	.11	0	0	.44	.33	0	0	.11
.1	0	.1	.1	.2	.1	.2	.1	.1
0	.11	0	0	.23	.05	.05	.35	.17
0	0	0	.05	.17	0	0	.17	.58

.53	.21	.07	.03	.03	0	0	.10	0
.09	.56	.04	.06	.13	.09	0	0	0
.05	.26	.52	.05	.05	.05	0	0	0
.16	0	0	.4	.2	.12	.12	0	0
.07	.10	.01	.08	.55	.07	0	.08	0
0	.03	.06	.03	.29	.35	0	.09	.12
.09	0	0	.09	.09	.09	.36	.18	.09
0	.07	0	0	.07	.07	.22	.37	.18
0	0	.04	0	0	.22	0	.13	.59

.48	.11	.03	.14	.14	0	.03	0	.03
.06	.59	.04	.06	.18	.02	.02	0	.02
.07	.30	.23	0	.23	.07	0	0	.07
.16	.06	.03	.36	.16	.06	.1	.03	0
.01	.09	.03	.07	.57	.06	.05	.03	.03
.05	.27	.05	.16	.11	.22	0	0	.11
0	0	0	.04	.20	0	.54	.12	.08
0	0	0	.07	.15	0	.15	.46	.15
0	0	.04	.09	.04	.22	.04	.09	.45

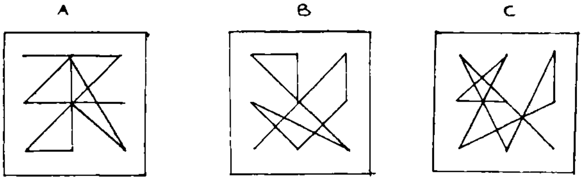
MATRICES OF PROBABILITY OF TRANSITION (FROM SEVERAL SUBJECTS)

A
ITERATION 23
.109 .190 .057 .095 .255 .072 .033 .082 .102

B
ITERATION 18
.110 .190 .057 .095 .255 .072 .033 .082 .102

C ITERATION 15
.110 .173 .006 .007 .208 .118 .004 .101 .093

FINAL EQUILIBRIUM



SIMULATION

From this visual exploration of several subjects we get a matrix of probability of transition on several levels from B1 to B2. The typical scanpath we obtain is shown in the 3 cases. We simulated the exploration from these matrices.

EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

LEXICONS AND EYE MOVEMENTS : AN INTERLANGUAGE APPROACH

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It is surprising to note that, while detailed theories are available about the structure of many languages, data are few as regards differences between comprehension mechanisms. Moreover, very few experiments have been attempted to tackle this problems via eye movement analysis. Such a lack may be deplored, as this approach allows us to study both global aspects of reading behaviour (reading time, gaze duration per word, number of regressions) and detailed eye movement characteristics (duration, length and position of fixations). Therefore, it is a perfectly suitable tool for a first approach in the field of interlanguage psycholinguistics.

What is the interest of the interlanguage approach ?

(1) First and in the most practical way, it allows better understanding of learning, comprehension and memorization mechanisms in different languages. This kind of knowledge is necessary in the field of applied psychology. For example, problems raised by technology transfer from one country to another are often related to man-machine communication. As this is gradually shifting from mechanical devices (buttons, levers,...) to natural languages (in writen or spoken forms) it is essential to master idiosyncratic differences in word meanings, strategies of visual search, the cultural role of written, spoken or gestual communications...

(2) Our models of language processing can be significantly enriched, indeed challenged if they take into account more general constraints in relation with other languages. For example, in order to study whether reading processes use phonological information to access the meaning of words, many interlanguage approaches have been attempted specially between English and Serbo-Croatian (Katz and Feldman, 1984), English and Chinese (Chen and Juola, 1982, Seidenberg, 1985) or in Hebrew with or without vowels (Koriat, 1985). Only this kind of approach allows the study of the relation between orthography and phonological encoding (or how writing systems represent phonology).

(3) The interlanguage methodology can be compared to the one used in the study of language pathology. In both cases, it is the comparison between two modes of processing that provides elements for working out new models. As Morton noted (Morton, 1981), the most important problem for cognitive psychologists lies in the way they develop theories rather than their experimental methodology. In many ways the extension of reading research to the field of psychopathology results in great improvements in lexical access models. The reader could for

example find in Marshall and Newcombe (1981) an example of such an approach related to computational theories. This comparative approach has also been used in the construction of algorithms for word recognition (specially with passive models like the "logogen model" of Morton (1979). Thus, we would stress the importance of both interlanguage and psychopathological approaches as a new way to develop theories of reading processes.

(4) As we can see, our models of reading are strongly dependent on linguistic theories used to describe language. For example, it is interesting to notice that in arabic the same word can be broken up into two, three, or four morphemes depending on the theory referred to (McCarthy, 1981, 1983). So, any oculomotor model using the morpheme notion as input variable will therefore be indissociable from the linguistic theory applied to describe the language.

The following pages feature a detailed description of the various writing systems used all over the world. A number of papers will then take up the study of the visual exploration mechanisms when reading in japanese, arabic, french and english. Finally, reading in pathological cases will provide a few examples of strategies used by readers to make up for particular visual defects.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

SYNCHRONIC DESCRIPTION OF PRESENT-DAY WRITING SYSTEMS: SOME IMPLICATIONS FOR READING RESEARCH[+]

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First, the characteristics of present-day writing systems are illustrated by describing how Chinese, Japanese, Korean, Hebrew, Arabic, and Hindi are conveyed by script. This is followed by a discussion about the nature of the linguistic units that are, or that should be represented by alphabetic scripts. The last part of this chapter is a brief description of the different lines of research bearing on how the reading processes are modulated by the properties of the writing systems.

INTRODUCTION

The first of the two sections of this chapter is aimed at describing the main present-day writing systems as a function of the relationship between the written symbols and the linguistic units they represent. From the standpoint of a cognitive psychologist interested in reading processes, it is almost natural to emphasize a synchronic rather than a diachronic approach to writing systems. This is because it is unlikely that in reading a person brings to bear much knowledge about how the script has evolved to reach its present state of perfectness or imperfectness. The second section elaborates on the first in dealing with orthographic representations and in outlining how the cognitive psychological (and neuropsychological) approach to reading became interested in investigating the reading processes in different writing systems.

Anybody interested in writing systems would be struck by the lack of recent general surveys of this topic. Standard references are Diringer (1968) and Gelb (1963) in English and Cohen (1958) and Février (1959) in French. One should not be misled by these publication years that, except for Cohen, correspond to revised editions of books basically summarizing the state of the art before World War II or a little later. All these books reflect outstanding scholarship in the historical and descriptive aspects of writing systems, and Cohen (1958) and Gelb (1963) should even be credited for going far beyond this exclusive point of view. Cohen's (1958, Chapter 10) treatment of orthographies in many alphabetic languages has plenty of insightful distinctions and observations still worth reading for those more concerned with linguistic aspects of writing. Gelb (1963) was even more ambitious in aiming at laying the foundations of a science of writing. In the course of doing so, Gelb made several personal theoretical choices, some of which were judged highly controversial by many of his peers. This point should be kept in mind because, during the last 30 years, Gelb's book has become the standard reference in the field. As such, it exerted a nonnegligible influence on the cognitive psychology of reading, for instance in shaping some of the ideas developed by Gleitman and

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[+] Preparation of this chapter was supported by the Research Council of this University and by the Ministry of Scientific Policy (Action de Recherche Concertée "Processus Cognitifs dans la Lecture").

Rozin (1977 ; Rozin & Gleitman, 1977) in two very influential papers. I shall come back to this point in the second section. There is no recent, general survey with the scope and comprehensiveness of those I have just mentioned (or of Menninger, 1969, in the related topic of number writing) and, sadly, it is likely that our new scientific habits will no longer encourage such books to be written.

With respect to theory and terminology, two chapters in a book edited by Haas should be mentioned ; one by Pulgram (1976) is concerned with typologies of writing systems, and the other by Haas (1976) deals with the basic options in designing writing systems. Very recently, a new book by Sampson (1985) was published that deserves to become a standard reference in the field, at least among cognitive scientists. From the vantage point of the linguist, Sampson succeeds in integrating typological, historical, and psychological aspects of writing systems to a degree never reached before.

Space limitation prevents an in-depth discussion of terminology and definition. To a large extent, I shall adopt Sampson's hierarchical (1985, p. 32) classificatory scheme, which is a satisfactory synthesis of concepts developed by Gelb (1963), Haas (1976), and Pulgram (1976).

The first major distinction is between semasiographic and glottographic visual systems of communication. A semasiographic message conveys meaning directly without mediation of the spoken language. Semasiographic messages were generally vague when they were first used in primitive societies, but modern semasiography as it is used in specialized domains such as road signs or mathematical notation conveys highly specific, precise messages. The cardinal feature of a semasiographic message is that it does not translate into a single sentence of the spoken language. In contrast, a glottographic message represents an actual or a potential spoken utterance. In his initial broadest possible definition of writing as "a system of human intercommunication by means of conventional visible marks" Gelb (1963, p. 12) did not distinguish between semasiography and glottography. But he went on to restrict writing to glottographic systems, coming close to the conception of Bloomfield (1933, p. 21) who claimed that "writing is not a language, but merely a way of recording language by means of visible marks". A minor addition to these definitions is needed to avoid any visual message, such as nonverbal meaningful gestures or finger spelling, to be considered writing ; namely, the visible marks must be made permanent on some traditional support (stone, wood, paper, leather, etc)[1].

Glottographic systems being the only ones to provide full writing, any further distinction in the classification will be restricted to them. Recording language by means of visible marks requires establishing some kind of isomorphism between the phonic medium and the graphic medium. This could theoretically be achieved in many different ways, but actualizations have taken only four different forms. Mapping between the two media has been implemented by segmenting the spoken utterance into words, morphemes, syllables, or phonemes and by associating these units with conventional graphic symbols henceforth referred to as graphemes[2]. It is convenient to consider an intermediate level in the classification in which glottographic writing systems based on meaningful units (words or morphemes) are subsumed under the logographic heading and those based on meaningless, phonological units, either syllables (syllabic systems) or phonemes (alphabetic systems), under the phonographic one. Three points should be made to further specify some terminological distinctions.

1. The term logography has replaced the older term ideography that became inappropriate as soon as one recognized the glottographic essence of writing systems. What is represented in writing is not the concept itself (or the idea), but the word standing for the concept. To keep strictly in line with etymology, the term logographic should designate only writing systems whose units are words. We could then use the term morphographic for those systems representing morphemes. This would force us to find a new header for replacing the logographic one, but little would be gained in doing so. Besides, it would not help us much in specifying exactly

what is represented in the Chinese script, the only one to be extensively based on a logographic principle. As we shall see, Chinese graphemes stand for monomorphemic words and the notion of plurimorphemic word is not as distinct from that of syntactic construction as it is in English, for example.

2. Number writing is semasiographic, not glottographic, because symbols used in the positional notation do not translate a spoken utterance (e.g., 3,125 stands for three thousand, one hundred and twenty-five). There is nevertheless a widespread tendency among cognitive psychologists, including myself in another article (Holender & Peereman, 1985), to consider single digits as logograms. This is not necessarily an appropriate terminological choice as suggested by Edgerton (1941) in a brief, insightful article. The point raised by Edgerton is that even single digits do not always have an exact correspondance in a spoken utterance (e.g., 2 is not pronounced in reading *2nd* ; word order is reversed in reading *$3*). Hence, from a formal point of view, it is better to classify digits under the semasiographic heading in all circumstances.

3. An alphabetic script establishes a relation between graphemes and abstract units of the spoken language called phonemes, not between graphemes and speech sounds. If the latter were the case, an alphabetic script would be equivalent to the International Phonetic Alphabet (IPA), which is never the case. Phonetic differences such as that between the aspirated [t] in [top] and the unaspirated [t] in [stop] are not represented by the orthography unless they have a functional contrastive value in the language ; that is, unless they differentiate between phonemes. This is not to say that phonetic features are never represented at all, but they are neither systematically represented nor used as basic units in any phonographic writing system. A similar claim can be made as regards suprasegmental phonology (e.g., stress, intonation) that is poorly, if at all, represented in writing.

The following conventions will be used. A word between double quotes refers to a linguistic form irrespective of the medium. An italic word refers to the written form. As usual, phonetic representations are between brackets and phonemic ones between slant lines, but I shall keep on using the Latin alphabet, supplementing it with verbal descriptions if necessary, instead of using the IPA symbols.

PRESENT-DAY WRITING SYSTEMS

Nonalphabetic Scripts

Chinese. The standard references are Kratochvíl (1968) for the language and Alleton (1976) for the writing system. As regards writing, shorter treatments by French (1976), Leong (1973), and Wang (1973) provide us with excellent introductions to the topic.

Chinese is not a unitary language ; it can be divided into several groups of dialects all belonging to the Sino-Tibetan language family. Mandarin is the most widespread group of Chinese dialects of which one variety spoken in the area of Peking is now considered Modern Standard Chinese in Mainland China. What should be understood by this concept is probably well captured in the following quotation from Kratochvíl (1968, p. 21) : "the language used today by educated speakers of Peking dialect which most speakers of other Chinese dialects consider as the 'correct' form of oral communication and in whose favour they adjust their own speech behavior". Yué dialects are spoken in Hong Kong and in the area of Canton and also by the majority of the Chinese people living in the United States because their ancestors generally came from the Canton area (Wang, 1973). In Taiwan, people speak dialects of the Mín group.

Typologically, Chinese is an isolating language. Many words are free, invariable root morphemes that are never inflected. There is also a limited number of bound morphemes never used in isolation, but serving as affixes associated with root morphemes. Plurimorphemic words are often dimorphemic. In this latter case words consist of a rigid arrangement of either two root morphemes or of a root morpheme and a bound morpheme. Kratochvíl (1968, Footnote p. 73) writes that "MSC [Modern Standard Chinese] morphology is up to a point petrified earlier syntax". The boundary between syntax and morphology is therefore not very easy to draw in Chinese.

Chinese syllabic structure is relatively simple, which entails that only a few hundreds of syllables exist in the language. Though ancient Chinese probably had a repertory of over a thousand of syllables, modern Mandarin has only a stock of about 420 such elements (Alleton, 1976 ; Leong, 1973). Allowing V to stand for a single vowel, a diphthong or a triphthong, only V, CV, VC, and CVC syllables are represented in modern Chinese. This basic syllabic stock is nearly four times as big (1,380 syllables according to Diringer, 1968, p. 64) because almost every syllable can be pronounced with one of four distinctive tones[3]. In Chinese, a tone change (e.g., /mā/ with a high vs. /mà/ with a falling tone) is as distinctive as a consonant change (/mā/ vs. /pā/) or a vowel change (/mā/ vs. /mī/).

The cardinal structural feature of Chinese is that almost every possible syllable is a morpheme and almost every such morpheme is also a word. Even in allowing for widespread homophony--about 80 % of the monomorphemic words have at least one homophone (French, 1976, p. 105)--the basic stock of nearly 1,400 syllables is not large enough to yield all the words required by the language. This entails that many words are plurimorphemic, often dimorphemic (hence disyllabic) as was already stressed above.

Chinese graphemes, generally called characters, map onto speech at the morphemic level. Hence, strictly speaking, the Chinese script is morphographic. However, as point 1 in the *Introduction* entails, using the logographic label is more convenient in our classificatory scheme. Aside from a few exceptions (mainly bound morphemes), there is a one-to-one correspondance between characters and monomorphemic words. Compound words are therefore represented with the appropriate number of characters, each one corresponding to one constituent morpheme. Let us summarize what has been described thus far by stating that in Chinese there is almost a one-to-one relationship between the elements of any two of the four following sets : syllables, morphemes, monomorphemic words, and characters.

Structurally, characters can be classified into two main groups, one consisting of simple characters and the other of compound characters. The make-up of simple characters is a variable number of strokes whose configuration cannot be analysed into functional subcomponents. Many of them have a pictographic origin that is now lost through simplification and stylization. A few of them are diagrams concretizing more or less abstract concepts (e.g., one, two, or three horizontal strokes standing for the numerals 1, 2, and 3). There are about a thousand simple characters in use at the present time.

Compound characters are of two types. There is a small subset of characters composed of two or three simple characters and whose meaning is derived from the meaning of the subcomponents. However, most of the compound characters (probably about 80 % of the characters in use), are phonetic compounds. One such character consists of two parts ; one, called the radical, suggests the meaning of the character, and the other, called the *phonetic*, suggests its pronunciation. There are 214 radicals (now reduced to 189 in Mainland China), most of which are simple characters that can be used either in isolation or, in some cases, as *phonetics* in other characters. *Phonetics* are often simple characters, but some of them are themselves phonetic compounds. One can identify 1260 such *phonetics* (Alleton, 1976, p. 36).

Two qualifications should be made about phonetic compounds. First, the radical may sometimes provide an accurate indication of the meaning of a character, but often the semantic relation between the radical and the character is very loose and even, in some cases, misleading. Second, a similar situation prevails with respect to the relation between pronunciation of the phonetic part of such a character and pronunciation of the character itself. Sometimes homophony or near homophony (the tone is generally neglected in building these associations) is the rule, sometimes great differences between pronunciations exist, mainly because words once pronounced the same have followed different paths of phonetic transformation.

Whether simple or compound, characters always occupy roughly the same square area in a text. There is no space between characters, hence no visual cues demarcating plurimorphemic words, but Western punctuation marks are now commonly used to separate clauses and sentences. Chinese is written either in columns to be read from top to bottom and from right to left or in rows to be read from left to right.

Chinese morphographic script is well suited for writing the invariable monosyllabic morphemes of the Chinese language. One of its main advantages is to provide an easy means of disambiguating homophones in writing. This could hardly be realized by using an alphabetic script (even allowing for a lot of irregularity in the grapheme-phoneme correspondance such as in the French homophones *mer*, *mère*, *maire*, for example) because homophony is so widespread in Chinese that it allows complete short homophonous sentences to be written (a trick sometimes used for greeting purposes, see Sung, 1979). One of the main drawbacks of Chinese script is the difficulty of writing foreign proper names (Sampson, 1985, pp. 166-167). Such words are first given a Chinese syllabic rendition that is then transliterated using characters having the appropriate pronunciation, their meaning being generally disregarded (e.g., *Marx* = *mǎkèsī*). There is no particular subset of Chinese characters used as a syllabary, but the choice of characters playing the role of *phonetic loans* is smaller than the full repertory. In analysing the writing of 200 foreign names appearing in Hong Kong newspapers (seven different newspapers in a four-day period), Godwin (1979) found 267 different characters used for representing 193 different syllables, of which 52 were associated with more than one character.

There is no doubt that mastering Chinese reading and writing requires a considerable amount of rote leaning. There is, however, a widespread tendency in the West to exaggerate the burden imposed by the Chinese script. Besides, the saliency, in terms of linguistic awareness (see the second section, below), of the monosyllabic morphemes represented by Chinese graphemes probably makes the writing system easy, if not quick, to learn.

How many characters should a Chinese person know to become a reasonably proficient reader ? Different sources provide an estimate of 2,000 to 3,000 characters corresponding to the standard of elementary education. In reviewing thirty years of teaching studies taking place before 1949, Ai (1950) reported that an average student knew about 2,000 characters by the end of his four-year primary courses. Similarly, in Hong Kong, children learn from 500 to 600 characters each year, thereby acquiring a total of about 3,000 to 3,500 characters after six years of primary school (Leong, 1973). According to Leong, only a quarter of the schooling time (plus a fair amount of daily homework) is devoted to this topic. In Mainland China, there is an official list of 2,421 characters everyone should know. Current dictionaries often comprise less than ten thousand characters[4] (Ai, 1950 ; Alleton, 1976). Different sources agree in estimating that an adult of average education reading newspapers probably knows about 5,000 characters, which implies an ability to read about three times as many words (Ai, 1950 ; Alleton, 1976 ; French, 1976) because many words are plurimorphemic.

Japanese and Korean. The standard reference about Japanese language is Miller (1967). A special issue of *Visible Language* edited by Seeley (1984a) is devoted to some aspects of the Japanese writing system. In the psychological literature, Morton and Sasanuma (1984) provide a good sketch of Japanese writing and Taylor (1980) does the same for Korean ; Sakamoto (1980) gives an excellent description of *hiragana*.

For historico-political reasons, a large stock of Chinese morphemes were incorporated into both the Korean and the Japanese spoken languages. These languages belong neither to the same family (Korean is an Altaic language, but whether Japanese also belongs to this family is still controversial) nor to the same typology as Chinese (Korean is agglutinative and Japanese inflexional). Words, and even root morphemes, are often plurisyllabic. These languages differ, however, in the complexity of their syllabic structure. Japanese has only a little over 100 open syllables of the types CV and V and some CV syllables containing a glide. In contrast, Korean has several thousands of syllables of the following types : V, VC, CV, CVC, and CVCC. Writing both of these languages using exclusively Chinese characters standing for their morphemic value would be inadequate because affixes, grammatical inflexions, and function words could simply not be represented. The solution adopted in both Japanese and Korean consists in writing the roots of content words (nouns, adjectives, and verbs) with the corresponding Chinese characters and to supplement this incomplete system with either a syllabary (Japanese) or an alphabet (Korean) to represent all the rest. Such is the principle, but, as we shall see shortly, its implementation is much more complex, especially in Japanese.

To begin with, let us describe the phonographic part of these systems. Japanese's two *kana* scripts, *hiragana* and *katakana*, are complete syllabaries, either of which could be used to write any Japanese word, whether of native or foreign (including Chinese) origin. There is a one-to-one correspondance, similar to that between upper and lowercase letters in our alphabet, between the graphemes in the two *kana*.

There are 46 basic *kana* graphemes ; five corresponding to the vowels /a, i, u, e, o/, one to the nasal phoneme /n/, and the rest to open CV syllables of which the consonants are /k, s, t, n, h, m, y, r, w/ and the vowels any of the five vowels just mentioned. The syllables /yi, ye, wi, wu, we/ are not represented ; some because they never existed in the language, others because they are no longer in use today. Twenty-five additional syllables are represented by adding one of two diacritics to the upper right side of some of the basic characters. A small circle transforms /h/ into /p/. Two ticks transform /k, s, t, h/ into their voiced counterparts /g, z, d, b/. Thirty-three syllables containing a glide (e.g., /nyo/ or /kyu/) are written with two characters, one corresponding to the syllable beginning with the appropriate consonant followed by an /i/, and the second being a small version of the character for /ya/, /yo/ or /yu/ (Hence, *nyo* is *ni* + small *yo* and *kyu* is *ki* + small *yu*). There is one other small character used to indicate gemination of any consonant.

The Japanese grapheme-syllable correspondance is regular, except for at least five cases (see Sakamoto, 1980). One such case is that in the middle of a word, the phonetic value of [n] changes into [m] if the following phoneme is /m/, /b/, or /p/, but the same grapheme is used in both cases. Two other cases are that the *kana* for the vowels /u/ and /i/ should be pronounced as if they were standing for /o/, and /e/ when they are used to prolong the sound of syllables ending by /o/ and /e/. Two further cases involve the grammatical particles /wa/ and /e/ that are written with the graphemes usually standing for /ha/ and /he/ ; this being an example of historical orthography.

Although it is quite convenient from a typological point of view to consider the two *kana* as syllabic scripts, this terminology is only roughly appropriate. The point is that *kana* symbols stand for pronunciation units of approximately the same duration. These phonological segments are called moras. In Japanese, moras are not always coextensive with syllables, the most prominent exception being the sound [n], which is a mora, but not a syllable. This distinction is best captured by an example. A word such as "ningen" (human being) has two syllables (/nin/ and /gen/), but four moras (/ni/, /n/, /ge/, and /n/) ; it is accordingly written with four *kana*.

The Korean phonographic component could not be syllabic because syllables are too numerous. Therefore, an alphabetic principle is used. Only 24 basic letters are needed to represent the phonemes of Korean (Taylor, 1980) ; 14 standing for the consonants and 10 standing for the vowels[5]. These alphabetical symbols are always grouped into syllabic blocks containing as many letters as there are phonemes in the syllable (from 1 to 4) except that the absence of initial consonant in a V or a VC syllable is indicated by a small circle. Letters are organized in both the horizontal and vertical dimensions of a syllabic block according to simple rules. Knowing these rules and the basic alphabetic symbols allows a person to read any syllabic block and hence any plurisyllabic word written phonographically (not including a logographically represented root).

The logographic component of the Japanese script consists of *kanji* characters. A *kanji* character is a borrowed Chinese character standing for a Japanese native root morpheme having roughly the same meaning as that originally represented in Chinese. If this were all, the system would be relatively simple. Complications arise from two sources. First, many Chinese words were incorporated into Japanese, forming the Sino-Japanese vocabulary. This implies that the Japanese spoken language which, as any language, is of course able to express any current concept with native words, often has Sino-Japanese synonyms or near-synonyms to express the same concepts. Sino-Japanese words are naturally represented with the original Chinese characters. It follows that most characters have at least two different "readings", one called the *kun*-reading, corresponding to the Japanese native morpheme, and the other, called the *on*-reading, corresponding to the Sino-Japanese form of the same morpheme. Second, there are three different layers of Chinese words in Japanese, each layer originating in a different period of borrowing (roughly, 6th, 8th, and 14th century A.D. : see Miller, 1967, Chapter 3). Chinese pronunciation rules were different during each of these periods. Even though the vocabulary borrowed during each of these three periods is more or less disjoint, there are, however, some characters having two or even three different *on*-readings, the correct reading being determined contextually (see Sampson, 1985, Chapter 8 for more details).

The pronunciation of a Sino-Japanese word consists in the Japanese rendition of the corresponding Chinese pronunciation at the time of borrowing. Relative to Chinese, tone is always suppressed, which implies that homophony is extremely high in monosyllabic Sino-Japanese words (less than 300 different forms exist), and sound modifications are frequent because Japanese phonology is different from that of Chinese. All this implies that the phonetic part of a compound character, which can of course play no phonetic role at all in the *kun*-reading of the character, is probably not playing a much greater phonetic role in the *on*-reading(s) of the same character either.

Pronunciation of the *kanji* part of the script is contextually determined. Generally, isolated *kanji* are given a *kun*-reading, whereas *kanji* occurring in compound words are given an *on*-reading. Which particular *on*-reading is appropriate when there is more than one possibility can be determined by subtle meaning distinctions conveyed by the compound. *kanji* completed by *kana* indicating inflexions are always given a *kun*-reading. No such complications exist for the logographic part of the Korean script because there is only one possible pronunciation which is quite close the Chinese one (Taylor, 1980).

The Japanese script is, therefore, a mixed script combining logographic and phonographic representations. Content root morphemes are written in *kanji* ; inflexions, function words, affixes, and other grammatical particles are written in *hiragana* ; foreign, non Chinese, loan words are written in *katakana*. Also, Arabic numerals are now commonly used to write numbers, and uppercase Latin letters appear in Japanese texts for common international abbreviations.

Like Chinese, Japanese is written either in columns to be read from top to bottom and from right to left, or in rows to be read from left to right. Word boundaries are not indicated but the more complex visual configuration of *kanji* compared to *kana* graphemes provides a good visual cue for root morpheme identification. Also, a transition from *hiragana* to *kanji* must represent a word boundary because there are almost no prefixes in Japanese (Sampson, 1985, p. 186). The Western full stop and comma are now commonly used (see Twine, 1984).

The main advantage of the logographic part of the Japanese script is to allow for disambiguation of homophones, which is even more necessary in Japanese than in Chinese. Another advantage pointed out by Backhouse (1984, p. 223) is that the scientific vocabulary is transparent because it is built on Chinese roots which, once represented by the corresponding characters, could evoke their more or less synonymous meaning in native Japanese. For these and other reasons, it is extremely unlikely that the Japanese would ever drop the logographic component of their script. Assuming they do nevertheless abandon it, there is no reason (at least, no linguistic reason), in view of the simplicity of the syllabic structure and of the associated *kana* syllabic script, that Japanese should ever switch to an alphabetic script. Notice, however, that Miller (1967, p. 98) states that "it was the nature of the script which was borrowed, rather than the structure of the language to which is was now adapted, which determined the syllabic nature of Japanese orthography".

Before World War II, a Japanese reader should probably have known as many (5,000 or so) *kanji* characters as a Chinese reader. The situation has changed since 1946 because the *kanji* repertory has been limited to an official list of 1,850 characters (see Seeley, 1984b for a history of changes in the Japanese script since 1900), of which 881 (996 since 1971) are supposed to be learned by the end of primary school (Sakamoto & Makita, 1973). A revised list published in 1981 now contains 1,945 characters, of which 737 have only *on*-readings, 40 have only *kun*-readings and 1,168 have both *on* and *kun*-readings (Backhouse, 1984). The official list of *kanji* characters represents the minimum educational standard and newspapers are requested not to use characters outside the list. This is not so in scientific or literary texts so that, even now, Japanese educated readers probably know over 3,000 characters. In North Korea, the use of Chinese characters has been abandoned completely, whereas in South Korea 1,300 such characters are still used in combination with the alphabetic-syllabic script (Taylor, 1980).

Alphabetic Scripts

The alphabetic principle is used in almost all the written languages of the world save for those we have just discussed. Ideally, an alphabet should contain as many graphemes as there are phonemes in the spoken language and a one-to-one correspondance should be established between graphemes and phonemes. Although this ideal is almost never reached completely, it is often approximated quite closely. It is worth distinguishing different types of departures from this principle because they are not all equally damaging to it. One type of departure consists in using polygraphs. A polygraph is a combination of two or more graphemes of the repertory standing for one single phoneme. As long as these graphemic groups are consistently mapped onto the same phonemes, their use only slightly violates the basic principle, if at all. A little more damaging is the existence of consistent, but contextually determined values of some graphemes (e.g., the value of *c* before *e* and *i* vs. its value before *a*, *o*, and *u* in English or in French). Finally, the most damaging departure is achieved when the one-to-one grapheme-phoneme correspondance is abolished for reasons unrelated to contextual letters. In this case, one grapheme (or polygraph) may represent several phonemes or one phoneme may be represented by more than one grapheme, or both. Some reasons why such a violation of the basic alphabetic principle can occur will be examined in the second section of this chapter.

In what follows I shall provide some broad historical information (based almost exclusively on Diringer's 1968 account) to explain how alphabetic writing spread all over the world. There is general agreement about the fact that the alphabetic writing principle evolved only once in history. There is, however, much controversy about the stages (and the influences involved) of the process, taking several centuries, which led to the first complete alphabet : the North Semitic alphabet (called West Semitic syllabary by Gelb, 1963). One of the oldest famous inscriptions using this alphabet, that of Ahiram's coffin, is now dated as stemming from the early tenth century B.C. (rather than from the late thirteen century B.C. as believed before, see e.g. Gelb, 1963, p. 132 ; Harden, 1971, p. 108). The North Semitic alphabet, with its 22 letters representing only consonants, is the prototype of all the alphabets in the world. It is convenient to distinguish three main branches in the spreading of alphabetic scripts ; these are the Aramaic, the Brahmi, and the Greek branches. Aside from their different geographical distribution, which is irrelevant for our purposes, these three groups of alphabets differ mainly with respect to how fully and by which graphical device they represent vowels.

Aramaic branch : Hebrew and Arabic alphabets. Starting in the seventh century B.C. and lasting for more than a thousand years, Aramaic, a Semitic language from Syria, became the *lingua franca* of the Near East, extending as far as West India. Aramaic was written with a graphically modified version of the North Semitic alphabet. The Aramaic script is at the origin of both the classical "square Hebrew" alphabet and the Arabic alphabet. Numerous classical Hebrew inscriptions can be found in the second century B.C. and the earliest Arabic ones appeared in the fifth or sixth century A.D.

The principle of Semitic writing is to represent fully the consonants and to leave the vowels either unmarked (originally) or incompletely marked as is the case in most Hebrew and Arabic texts today. Two features of the Semitic language structure are probably responsible for the fact that a script based on such a principle can work. First, the phonological make-up of a root morpheme is generally not concentrated into one unitary speech segment. Rather, being embodied in the consonantal skeleton of a word-size utterance, this make-up is discontinuously spread throughout the spoken word. Second, the vowels interspersed within such a consonantal skeleton are used as inflexional patterns indicating, for instance, part of speech, verb tense and mood, and so on. Hence, a given consonantal pattern (often comprising three consonants) corresponds to a whole group of words related in meaning. In the case of an isolated word, providing the vowels (as is done in spoken language) would generally unambiguously indicate which word is intended. Conversely, in reading a text, contextual syntactic and semantic information together with the consonantal skeleton of a given word would, theoretically, unambiguously determine which word it is, thereby indicating which vowels to pronounce in the case of oral reading (see Barr, 1976).

Actually, reading a Semitic text completely devoid of vowels is not as easy as the foregoing description might erroneously suggest. It would require considerable grammatical knowledge and a cumbersome, long semantic and syntactic analysis would be necessary to reach a correct interpretation. For these and other reasons two ways of indicating vowels have been devised. One system, by far the most widespread, consists in providing partial vocalic information by using *matres lectionis* ; that is to say, letters of the repertory that could stand either for consonants or for long vowels according to the context. This system, though generally helpful, may nevertheless constitute a source of ambiguity in its own right because some letters play a dual function. The second system for specifying vowels consists in adding diacritics to the consonants. This optional practice is generally referred to as "pointing" and a text could therefore be "pointed" (containing both *matres lectionis* and diacritics) or "unpointed" (containing only *matres lectionis*). These diacritics are used not only for supplying full vocalic information, but also for completing missing consonantal information. There is no such practice as partial pointing ; hence, an unpointed text lacks both the vocalic and the consonantal information conveyed by diacritics.

Rosén (1977) provides a linguistic analysis of the contemporary Hebrew spoken language. As regards writing, Barr (1976), and especially Rabin (1977) are good sources and Navon and Shimron (1984) give us an excellent psychologically (from an information-processing point of view) oriented description of the main features of present-day Hebrew script.

Unpointed Hebrew is written with the 22 original consonantal letters derived from the Aramaic alphabet. Some letters stand for two different phonemes. Conversely, some earlier phonemic distinctions now lost in the spoken language are still orthographically represented ; hence, Hebrew orthography is historical.

Modern Hebrew has only five vowels (six in some pronunciations) /a, e, i, o, u/. The distinction between long and short vowels is now completely lost in speech, but not in writing. Rabin (1977) distinguishes between two types of unpointed spelling ; these are grammatical spelling and full spelling. Grammatical spelling uses three of the 22 basic letters as *matres lectionis* for supplying partial vocalic information about (former) long vowels exclusively. In this system, the letters *v* and *y* could stand either for their consonantal value or for one of two vocalic values (*v* stands for /o/ or for /u/ and *y* stands mostly for /i/ but sometimes also for /e/). A third *matres lectionis, h,* always indicates a vowel at the end of a word (generally /a/, sometimes /e/, and /i/ in a few cases) and a consonant elsewhere. Notice that grammatical spelling is completely standardized and consistent, also it is defective within its own logic in not being able to represent the long /a/ except in final position, and that it offers no graphical means of distinguishing between the vocalic and the consonantal roles of *v* and *y*. Full spelling adds two features to grammatical spelling. First *v* is now used for representing the (former) short vowels /o/ and /u/ and *y* for representing the short /i/. Second, the vocalic role of these two letters is now distinguished from their consonantal role by doubling the letters in this latter case. Notice that the use of full spelling is inconsistent and not standardized and that vowel representation is still ambiguous (many-to-one vowel-letter mapping) and incomplete because long /a/, short /a/, and short /e/ cannot be specified.

Most adult literature is unpointed. Pointing is used mainly in the Bible, children's books, and poetry. Children start learning to read with pointed texts, but they rapidly switch to unpointed ones. The pointing systems consists of a set of diacritics (placed above, below, or inside the consonants) aimed at supplying almost all the information missing in unpointed spelling. Pointing is quite successful in achieving this goal, but new problems may arise from the fact that the system is plethoric. For instance, there are 14 diacritics for indicating five vowels ; hence, here again Hebrew orthography pays its tribute to history. Diacritics are also used for distinguishing between cases in which the same letter could stand for two different consonants, for distinguishing between the vocalic and the consonantal value of *matres lectionis*, and for a few additional roles that will not be described here.

Hebrew is written from right to left, words are spaced, and letters are not very discriminable (square, noncursive shapes with few ascenders and descenders). Five letters have two different graphical versions, one being used only in initial and medial position and the other only in final position.

The basic principle of Arabic writing is the same as that of Hebrew. There are, however, some differences bearing mainly on details. The alphabet contains 29 letters standing for consonants only. Three of these letters are *matres lectionis* that are used consistently in unpointed spelling for specifying the three long vowels of Arabic /a, u, i/. Contrary to Hebrew, there is a one-to-one relationship between *matres lectionis* and long vowels in Arabic writing. In pointed spelling, the three other vowels of Arabic (short /a, u, i/) are marked by diacritics. There are two more diacritics, one used to indicate the absence of a vowel, and the other for consonantal gemination. On the whole, the Arabic pointing system is less complex than that of Hebrew due partly to the fact that all consonants are represented by basic symbols and partly to the small number of vowels.

Contrary to Hebrew, Arabic writing is extremely cursive. The basic shape of some letters are the same, but these are differentiated by using one, two, or three diacritical points. These diacritics are not optional and should not be confounded with those used in the pointing system described above. About three fourths of the letters have four different shapes according to whether they stand alone, or in initial, medial, or final position in a word. Arabic is written from right to left and words are separated by spaces.

The Brahmi branch : Devanagari alphabet. All the modern Indian alphabets derive from the Brahmi alphabet. This alphabet, appearing in the seventh century B.C., was probably adapted from the Aramaic alphabet (this hypothesis is favoured by Diringer, 1968, p. 262, though he admits that only the idea, not the script itself, could have been borrowed). Indian alphabets and their foreign offshoots in South East Asia, Indonesia, and Tibet are numerous. One of them called Devanagari (earliest inscriptions in the seventh century A.D.) plays a very important role in India because it was used for writing both Sanskrit (the historical literary language) and Hindi (the official language of modern India).

I took most of my information about Devanagari from Diringer (1968), Février (1959), and Oommen (1973). Devanagari has 48 letters : 34 consonants (plus a few additional borrowed consonants according to Oommen, 1973), 10 vowels, and 4 diphthongs. A consonant letter never has a pure consonantal value, but indicates the consonant followed by a short /a/, a very frequent vowel in the spoken language. This short /a/ is not pronounced in final position and becomes a *schwa* in unstressed syllables. The short /a/ is therefore indicated by default, whereas a vowel different from it is always fully specified by a small sign appended above, below, or to the side of the consonant. The value of a consonant letter accompanied by a vowel sign is therefore an open CV syllable whose vowel replaces the short /a/ of the basic letter. Two additional features are important. First, an initial vowel could not be represented in the system described thus far. This problem has been solved by designing vowel letters that are used only in initial position. Second, consonantal clusters are represented by grouping two or even three consonantal letters, which sometimes involves putting one letter on top of the other and modifying letter shape and integrity. There seems to be a large number of different consonantal clusters in Devanagari because, according to Février (1959, p. 348), 256 corresponding graphic patterns were available for printing at the "Imprimerie Nationale" in Paris. One diacritic indicates nasalization of the following vowel and another indicates less than full phonetic value of a letter (Oommen, 1973).

Devanagari is written from left to right and words are now separated by spaces. One feature common to all letters is a horizontal top line from which the other letter features hang. In addition to spacing, words are also individualized by the fact that the top line of the component letters is continuous.

One should not be misled by the syllabic appearance of the script. The principle that is applied is genuinely alphabetic, both consonants and vowels being completely represented by individual graphemes and a particular vowel sign having the same shape whatever the consonant to which it is appended (see Barr, 1976, pp. 72-74 for a similar claim about the Ethiopian script whose origin is the South Semitic alphabet rather than the Brahmi alphabet). Another point is that alphabets of Brahmi origin are not more defective in representing vowels than alphabets derived from Greek ; the difference between them being more of graphic than of linguistic import. Compared to those of Western alphabets, vowels (except in initial position) of Indian alphabets are smaller than consonants and not interleaved between consonants on the main line of text.

The Greek branch. The Greeks adapted the North Semitic alphabet in order to write their own language sometime during the first centuries of the first millennium B.C. (earliest inscriptions in the eighth century B.C.). All the alphabets used in European languages (and later in most languages spoken in the U.S.S.R.) are derived from Greek by mediation of either the Latin or the Cyrillic alphabet. The Greek's important innovation was the assignment of five unused Semitic letters to represent the vowels. They also added some letters to represent missing phonemes, ending up with the 24-letter classical Greek alphabet in the fourth century B.C. This alphabet was later modified by the Romans, who used 23 letters. Three letters were added in the Middle Ages, leading to the modern Latin alphabet of 26 letters used for all the languages of Western Europe and also by the Slavonic people of Roman Christian faith. The other Slavonic people, those of Greek Orthodox faith, have adapted the 43-letter Cyrillic alphabet that was designed on the Greek pattern in the ninth century A.D.

It is noteworthy that the Latin alphabet does not contain enough letters to represent all the phonemes of most West European languages. Because of the widespread reluctance to add new letters, the solution has often been to use polygraphs and to modify the values of some letters by adding diacritical marks. In contrast, the Cyrillic alphabet contains enough letters (sometimes, even too many letters) for a one-to-one grapheme-phoneme correspondance to hold true in most Slavonic alphabets derived from it. Also, after 1917, dozens of previously nonwritten languages in the U.S.S.R. were provided with alphabets containing enough letters to represent univocally each phoneme (this was first achieved by means of a modified Latin alphabet and then by switching to the Cyrillic alphabet during the Forties). As a consequence these alphabets often contain many more letters than we are used to. Amongst the 54 such alphabets listed by Diringer (1968, pp. 378-381), 37 have between 30 and 39 letters, 9 between 40 and 49 letters, and 8 between 50 and 73 letters.

Lack of space prevents me from describing specific scripts (see Cohen, 1958, Chapter 10 for many examples) originating from the Greek alphabet in any detail but some specific problems raised by some of them will be discussed in the next section.

ORTHOGRAPHIES AND READING RESEARCH

Orthographic Representations

In most languages the orthographic conventions are more complex than is suggested by simply describing the basic relation between graphemes and the linguistic units they generally stand for. Some reasons why this is so have already been touched on in the preceding section, albeit implicitly.

One complication arises from the mixture of different principles within a single text, the most extreme case being the mixture of phonograms and logograms in Japanese or in Korean. Such a mixture is not completely unknown in Western orthographies because a small number of nonalphabetic symbols such as £, \$, %, &, and Arabic numerals are sometimes encountered in alphabetically written texts. As was mentioned in the *Introduction*, numbers, even single-digit numbers, are best considered semasiograms and the logographic nature of some other symbols is also questionable (e.g., \$ and £ in \$*3* and £*7*).

What really complicates orthographic conventions, however, is the fact that the graphemes do not always keep their primary function. In Chinese, a basically logographic unit may sometimes take a phonographic value as is the case when it plays the role of a *phonetic* in a compound character or that of a *phonetic loan* for writing foreign proper names. Similarly, a string of letters may preserve the visual make-up of morphemes at the expense of loosing the phonemic values of some letters (e.g., *heal* vs. *health*) or words pronounced the same (homophones) may be differentiated orthographically (e.g., French *ver, verre, vers, vert,* and even so *vers* is a homograph with two meanings). One can, therefore, hardly specify what is represented in an orthography in terms of a single principle.

A good starting point for discussing these matters may be found in two citations, one from Gelb (1963) and the other from Chomsky (1970), offering as contrasting views as possible about what an ideal orthography should represent. Gelb reflects the linguistic *Zeitgeist* of the first half of this century in claiming that :

> what we should look for is a system of writing combining the exactness of the IPA alphabet with the formal simplicity of a shorthand system. (p. 246)

Whereas Chomsky (1970) believes that :

> an optimal orthography ... would be one that has as close a correspondance as possible, letter-to-segment, to the abstract lexical form. Such an orthography leads directly to the semantically and syntactically significant units, abstracting away from all phonetic properties that are determined by general rule. (p. 12)

Today, nobody would maintain that an orthography should be phonetic, but the underlying conception according to which an orthography should provide regular, consistent spelling-to-sound mapping rules is still widespread. As should be clear from the *Introduction*, this formulation is acceptable only if 'sound' is taken to mean any speech sound realizing the same phoneme. Gelb's original position in the above citation can accordingly be reformulated in the following terms without greatly altering its spirit : An optimal orthography should establish a regular, consistent correspondence between the graphemes (or grapheme strings) and the phonemes of a language (this will be referred to as Gelb's amended position from here on).

Chomsky's position stemmed from the generative theory of English phonology he developed with Halle (see Chomsky & Halle, 1968, pp. 49-50). The aim of this theory is to account for variations in the phonetic forms of words (e.g., "sign"-"signal", "divine"-"divinity", "courage"-"courageous") by postulating underlying invariant lexical representations and a set of ordered phonological rules for converting these representations into the appropriate phonetic representations. Chomsky believes (see above citation) that an optimal orthography should establish a point-by-point relation between letters and units of the underlying lexical representation, which is roughly what is achieved by English ; hence Chomsky's claim that "conventional orthography, in the case of English (or any other language of which I have any knowledge), is remarkably close to optimal in this sense" (Chomsky, 1970, p. 7).

It should be further pointed out that Chomsky's position rests also on the, needless to say, controversial assumption that some of the formal distinctions made by linguists have a "psychological reality" in the mind of a competent speaker-hearer/writer-reader. Chomsky postulates the psychological reality of only two types of representations--the lexical and the phonetic representations--departing from many other theorists in denying the existence of a phonemic level of representation. The phonological representation is composed of units more abstract than phonemes because they are defined in terms of both phonetic and morphemic properties (see Gleitman & Rozin, 1977). These units may be called morphophonemes and the lexical representation may be considered morphophonological, even though Chomsky avoids this terminology.

One supplementary hypothesis worth mentioning is that the lexical representation is assumed to be the same for every speaker of a language, even for speakers of different dialects, and to remain the same for long periods of time in spite of phonetic changes affecting the spoken language. This accounts for the adequacy of a single, stable orthography for representing different dialects and different stages of evolution of the spoken languages.

Recently, Mattingly (1984, see also I.Y. Liberman, A.M. Liberman, Mattingly & Shankweiler, 1980) has taken the argument further in attempting to demonstrate that orthographies are basically morphemic. According to this view, whatever the basic linguistic units represented by the graphemes, the ultimate goal of any orthography is to keep morphemic shape constant. This goal is, of course, automatically achieved in Chinese because it is a morphemic script. In phonographic scripts, the only way to fulfill this requirement would be to use an orthographic representation mapping the underlying morphophonological lexical representation as closely as possible. As explained above, this is basically what Chomsky believes orthographies do, but Mattingly introduces an important additional distinction, that between shallow and deep orthographies. A shallow orthography maps graphemes onto units corresponding to a broad phonetic transcription, units that are almost equivalent to phonemes as defined in Gelb's amended position. A deep orthography maps graphemes onto the morphophonemes of the underlying lexical representation. Languages may also be characterized by the shallowness or deepness of their phonology according to whether a small or a large number of phonological rules are needed to transform the lexical representation into the phonetic one. Of course, the deepness-shallowness dimension of both orthography and phonology is best conceived of as continuous, but, for the sake of simplicity, let us pursue the argumentation as if it were dichotomous. Combining deep and shallow orthographies with deep and shallow phonologies yields four possible outcomes. The crux of Mattingly's argumentation is that genuine shallow orthographies do not exist, or seldom exist. For him, it is most likely that what may look like a shallow orthography is determined by the shallowness of the phonology ; that is, by the fact that the lexical representation actually represented in the orthography is close to the phonetic representation.

Granting that one cannot hope to distinguish between shallow and deep orthographies in languages with shallow phonology, refuting Mattingly's hypothesis would require showing that languages with deep phonology do not necessarily have deep orthography. Here follow four lines of evidence casting doubt on the plausibility of the hypotheses of Chomsky (1970) and Mattingly (1984).

1. Historically, the basic goal in designing most alphabetic orthographies, including that of English, was to represent phonemes ; that is, to fulfill Gelb's amended position. The same tendency is pervasive when new orthographies are now adapted to unwritten languages (Berry, 1958, 1977 ; Tauli, 1977). Assuming that it is unlikely that in all these cases orthography is shallow because phonology is shallow, why then design phonemic orthographies if morphophonemic ones are more appropriate ?

2. Very few orthographies are explicitly designed to represent deep morphophonological structures, though O'Neil (1972) documents the recent (19th century) introduction of a morphemic, alphabetic orthography for Faroese. When orthographies happen to be deep, reforms tend to make them shallower. For example, the original Semitic scripts provided close to ideal morphophonemic orthographies, but they started loosing some of their perfectness in this respect when the decision was taken to indicate some vowels by means of *matres lectionis*. Moreover, full writing of the predictable vowels is even supplied (by pointing) when correct interpretation must be guaranteed (e.g., in the Bible or in poetry). Similarly, in Japanese, the often predictable change of a morpheme's initial unvoiced consonant into its voiced counterpart when the morpheme is the second of a compound (e.g., /kana/ becoming /gana/ in /hiragana/) was not marked in the orthography before, but it is now always indicated by a diacritic. In this respect Mattingly's (1984, p. 16 ; I.Y. Liberman et al., 1980, p. 147) assertion that this predictable change is not marked in *kana* is incorrect, probably because it is based on a

confusing description of Martin (1972, p. 93). It is clear that the *kana* component of the Japanese script is shallow, not deep as Mattingly believes (see Miller, 1967, pp. 194-196 ; Sampson, 1985, p. 186). This is, of course, not to deny that the Japanese orthography is highly morphemic, but it is so thanks to its logographic, not to its phonographic, component. Notice, however, that the voicing of the initial phoneme of morphemes occupying the second position in compounds is no longer always predictable in modern Japanese (indeed, /kana/ gives /hiragana/, but also /katakana/). Hence, one could argue that this unpredictability is responsible for the shallowing of an otherwise deep orthographic convention, just as the predictable vowels are now indicated in Turkish orthography perhaps because many borrowed words do not respect the rules of Vowel Harmony (Mattingly, 1984, p. 16). The present argument would, of course, be considerably weakened if this hypothesis were correct. But one could equally argue that if a deep orthographic principle were so desirable, the use of a shallower orthography could well be confined to borrowed words that, in any case, can generally be easily differentiated from native words. Indeed, English orthography, though containing many borrowed words, remains a deep orthography as regards Vowel Shift in the native vocabulary (I.Y. Liberman et al., 1980, p. 147).

3. Spelling-pronunciation, the tendency to pronounce words as they are written, is a phenomenon opposite to that described in point 2. When spelling and pronunciation become discrepant with respect to grapheme-phoneme mapping rules, instead of writing what is actually pronounced by changing the orthography, one can equally pronounce what is actually written. The spelling-pronunciation phenomenon is well documented by Levitt (1968, 1978) for English, French, German, Italian, and Spanish. It seems, therefore, that the underlying intuition of the speaker-hearer/writer-reader is that spelling should be phonemic (Gelb's amended position). Moreover, spelling-pronunciation may affect directly the form of the lexical representation and, more generally, orthography may shape the lexical representation even when spelling-pronunciation does not occur (Skousen, 1982). It is not clear to me how such phenomena could be reconciled with Chomsky's position.

4. Chomsky's claim about English orthography has been criticized on several grounds (Francis, 1970 ; Lotz, 1972 ; Tauli, 1977 ; see Sampson, 1985, Chapter 10 for a reappraisal). Even if the description of English orthography is more or less acceptable, one should be very cautious in interpreting Chomsky's (1970, p. 7) sibylline claim about "any other languages" he knows because the suggested generalization, though not studied systematically, is probably false. To take an example, it is often asserted that Schane (1968), in analysing French phonology and morphology, reached a conclusion similar to that of Chomsky for English as regards French orthography. This is hardly so. It is true that Schane (1968, p. 16) wrote that "French spelling, to a large extent, is highly morphophonemic" but he did so in the context of the analysis of French elision and liaison and he could hardly have concluded the same (indeed, he did not, but he eschewed the problem completely) after analysing the vowel and the verb system of French. Moreover, even in the context of elision and liaison Schane (1968, p. 17) immediately qualified his assertion by providing an example for which "the form is representative of a stage of derivation between the morphophonemic and the phonemic or phonetic levels". It is clear that admitting that intermediate levels of phonological derivation may be consistently represented in the orthography amounts to refuting Chomsky's position. One final point that deserves consideration is that although it is unlikely (but this should, of course, be investigated) that French phonology is shallower than English phonology as regards at least some cases of vowel alternation, it is nevertheless clear that French orthography is much shallower than English in transcribing many of the resulting phonetic (phonemic) distinctions (contrast English *divine-divinity*, *human-humanity* with French *divin-divinité*, *humain-humanité*, for instance). Similarly, Spanish, replete as it is with productive alternations such as *sentar-asiento*, *contar-cuento*, and so on, is certainly not particularly shallow phonologically though quite shallow orthographically.

Of course, impressionistic statements hardly constitute decisive arguments. Yet, in the light of the four lines of evidence just mentioned, I would conclude that one can hardly maintain the general claim (Mattingly, 1984) that orthographies aim at preserving the visual shape of morphemes, regardless of phonemic distinctions, which in alphabetic scripts implies that orthography should map onto the underlying morphophonological representations of morphemes (Chomsky, 1970 ; Chomsky & Halle, 1968). Even English orthography, which seems often to confirm this principle, also relies on other principles for representing language.

In a way, it is surprising that it took so long to recognize that English orthography is not unsystematic, but that it establishes regularities at different levels, which implies that it has to compromise between several incompatible tendencies. Bolinger (1946) and Vachek in the thirties (see Vachek 1945-1949, 1959, 1973 for English accounts) were among the first to point to the fact that English orthography often preserves the visual appearance of morphemes disregarding the phonemic changes if necessary (Bolinger, 1946 used the term "visual morphemes"). Venezky (1970b ; 1970c) has systematically studied the structure of English orthography, concluding that "English spelling-to-sound correspondences can be described in terms of patterns of graphemic, morphemic, syntactic, and phonotactical processes" (Venezky, 1970c, p. 127). Venezky (1970a), recognizing that it is advantageous for an orthography not to rely on a single principle, suggested that in designing new orthographies one should ponder the advantages of not relying exclusively on regular grapheme-to-phoneme correspondence rules.

It seems clear to me that the only reasonable research strategy would be to pursue Venezky's enterprise in English and in many other languages, coming up with a quantitative description of the proportion of cases in which the orthography is based on a phonemic (Gelb's amended position), a morphophonemic (Chomsky's position), and on other intermediate principles. Even though each of these orthographical principles is likely to be represented in at least some circumstances in most languages, alphabetically written languages should nevertheless differ greatly in the frequency of usage of each of these. Correlating the orthographical descriptions with structural descriptions of the languages (at least from phonological, morphological and morphophonological points of view) should help understand why this is so, which in turn could help generate interesting psychological hypotheses about how reading is achieved.

Reading Research

Lack of space prevents even thinking of establishing subtle distinctions or convergences between different reading research areas. To describe how a growing interest for reading in different writing systems evolved, I shall nevertheless adopt a trichotomic partition of the cognitive approach, distinguishing between a psycholinguistic, an information-processing, and a neuropsychological stream of research on the reading process. Two collections of chapters provide us with a wide coverage of this topic ; one was edited by Kavanagh and Venezky (1980) and the other by Henderson (1984). I shall conclude by some prospective considerations about the role eye movement monitoring may play in this research.

Psycholinguistic approach to reading. People working in this framework have been influenced to various degrees by Chomsky's theoretical positions as regards language acquisition and by his hypothesis described above about what should be represented in orthography. Related to these positions is the concept of linguistic awareness, whose theoretical aspects are developed by Mattingly (1972, 1979, 1984) and whose practical implications for research on reading development and reading disabilities can be well appreciated, for instance, in Gleitman and Rozin (1977 ; Rozin & Gleitman, 1977) and in I.Y. Liberman (1982 ; I.Y. Liberman et al., 1980).

The basic ideas are the following. First, analysing and describing how language is conveyed by script is of paramount importance. Second, reading is less natural than listening to speech. Reading is, therefore, a derived activity that, unlike speech processing, requires linguistic awareness, that is, an ability a person has to reflect upon his own linguistic activity. Third, most scripts represent phonological units, hence phonological awareness is the kind of awareness required for reading most scripts.

Linguistic awareness is necessary for learning to read because as I.Y. Liberman (1982, p. 58) explains : "any reader or writer must, at least, be able to abstract from the utterances of a language exactly those units that the orthographic characters represent". The problem is that not all these units are equally accessible, or equally salient. Though it is quite easy to abstract words or morphemes, it is more difficult to abstract syllables, and even more difficult to abstract phones[6]. Hence, in these terms the speech units idealized by alphabetic scripts are the most difficult to abstract from the phonic substance, probably because there are no such discrete units individualized in the speech stream. Though containing three phones a spoken utterance such as [big] is not composed of three successive units of sound equivalent, say, to three successive piano notes. Acoustic cues corresponding to each phone overlap in time through the whole syllable and abstracting phones from the speech stream requires a complex perceptual process, of which even the end-product is not always readily available to consciousness (A.L. Liberman, Cooper, Shankweiler & Studdert-Kennedy, 1967).

The ability to consciously abstract phones from the speech stream is nevertheless necessary to understand how an alphabetic script works. Conversely, this ability develops as a byproduct of learning to read an alphabetic script as the following results show. Suppose the task is to delete the first phone of spoken utterance such as /rapin/, thus answering with /apin/. It has been shown that children just beginning reading instruction (Alegria & Morais, 1979), adult illiterates (Morais, Cary, Alegria & Bertelson, 1979), and adult Chineses (Read, Zhang, Nie, & Ding, 1984)[7] reading logograms but not *pinyin*, all perform poorly ; whereas children after a few months of reading instruction, adults who became literate during adulthood, and adult Chineses knowing *pinyin*, all perform well (see Content, 1984 ; 1985 for a review of this research area).

One issue raised by Gleitman and Rozin (1977, Rozin & Gleitman, 1977) though somewhat tangential to the study of reading, is nevertheless relevant to the topic of this chapter. These authors surmised that the ontological development of the child may parallel the cultural development of humanity as regards the difficulty in abstracting the phonemes, adding a new example to the already long list of cases in which ontogeny is thought to recapitulate philogeny (see Gould, 1977, Chapter 5, for many such cases). The cultural part of the claim stemmed from an uncritical acceptance of Gelb's (1963) main thesis about the history of writing.

Gelb's thesis is that without borrowing, a writing system would always evolve by passing through three stages : logographic, syllabic, and alphabetic. Although a script may remain at an intermediate stage of development, it cannot skip stages. It is because he firmly believed in this thesis that Gelb denied the existence of consonantal graphemes in Egyptian hieroglyphs and in the Semitic scripts probably deriving from it. Gelb therefore considered these consonantal graphemes to be syllabic, not alphabetic, because an alphabet could not have evolved from a logography without first passing through an intermediate syllabic stage. Edgerton (1952) forcefully criticized this thesis in claiming that the alphabetic nature of some Egyptian consonantal hieroglyphs is uncontroversial among egyptologists and that Gelb's position is a pure example of *petitio principii*. Moreover, it is extremely unsatisfactory, at least in the dominant framework of segmental phonology, to consider a grapheme standing for a consonant followed by any vowel to be syllabic to the same extent as a true syllabic grapheme standing for a consonant followed by a specific vowel. Notice, however, that Gelb's claim that Semitic scripts are syllabic would have found a much better echo in the polysystemic approach to phonology advocated by Firth (1948) ; but this conception never played a prominent role in linguistics (see Lyons, 1962) and did not influence Gelb's thinking at all. Gelb also believed that not reaching the alphabetic stage is necessarily a mark of backwardness for a writing system. Again, Gelb's lack of linguistic considerations is responsible for his failure to appreciate how suited Chinese and Japanese scripts are to the structure of the languages they represent[8].

Information-processing approach to reading. Information-processing psychologists are interested in describing the nature of the mental representations involved, for instance, in recognizing, matching, or memorizing some stimuli. Various experimental techniques were developed during the late fifties and the sixties that were aimed at tracing the time-course of the flow of information and at probing the nature of transient intermediate representations used for processing. Starting in the early seventies a series of already classical experimental paradigms, and some new ones too, were adapted to fit the requirements of research on visual word recognition. Four main questions are currently investigated ; these are : (1) Is word recognition holistic or mediated by the identification of the constituent letters ? (2) What is the role of sentence context on word identification ? (3) What is the nature of the information used to access the mental lexicon, and related to it, how is pronunciation of a word achieved ? (4) What is the nature of the post-lexical memory code ? (See Henderson, 1982 for a very cogent discussion of the information-processing approach to reading).

Almost all this work has been carried out with native speakers of English, which implies that one cannot distinguish between those processing characteristics that are general and those that result from the idiosyncrasy of English orthography. There is, therefore, a growing body of research on word processing in alphabetic orthographies shallower than English, such as Serbo-Croatian (see Turvey, Feldman & Lukatela, 1984, for a review) or deeper than English, such as Hebrew (e.g., Bentin, Bargai & Katz, 1984). Comparison between pointed and unpointed Hebrew is of course of paramount importance in such an approach (e.g., Navon & Shimron, 1984) as is contrasting the effect of orthography on the same word processing tasks (e.g., English vs. Serbo-Croatian in Katz & Feldman, 1983). Thus far, the work on Chinese and Japanese have been carried out mainly in the framework of the investigation of hemispheric specialization (see Leong, Wong, Wong, & Hiscock, 1985 ; Peereman & Holender, 1985, for recent data and critical appraisals of this approach), but there is also some work on postlexical memory storage (e.g., Tzeng, Hung, & Wang, 1977). A good review of the information-processing approach to different orthographies can be found in Hung and Tzeng (1981).

Cognitive neuropsychological approach to reading. People working in this area use brain damaged patients showing different reading deficits as a source of information to build and corroborate functional information-processing models. Several different types of acquired dyslexias are now well documented in patients reading languages written in the Latin alphabet (mainly English and French), but Japanese patients showing a dissociation between the ability to read *kana* and *kanji* words are also extensively studied (Sasanuma, 1980 ; 1985). The cognitive neuropsychological approach to reading and its relation with the information-processing approach is best appreciated in the already classical *Deep dyslexia* book edited by Coltheart, Patterson, and Marshall (1980) and in its just published offspring, *Surface dyslexia* (Patterson, Marshall, & Coltheart, 1985). Paradis, Hagiwara, and Hildebrandt (1985) provide a similar account for Japanese reading.

Eye movements in reading. However justified is the interest for single word processing, one should nevertheless want to study the reading process in more natural settings than the usual laboratory situations. Eye movement monitoring offers itself as an ideal technique because it is both an on-line indicator of processing and a noninvasive methodology. Since the development of modern eye movement monitoring techniques in the mid-seventies, research has concentrated mainly on determining, for instance, the size of the perceptual span, the amount of information extracted from the parafovea, and how saccades are controlled. Relatively few studies have used eye movements as an indicator of ongoing linguistic processes in reading (with some prominent exceptions, e.g., Just & Cartpenter, 1980), but the situation is rapidly changing and new experimental paradigms and measurement techniques are now developed by investigators having a strong psycholinguistic orientation (e.g., K. Ehrlich & Rayner; 1983, S.F. Ehrlich & Rayner, 1981; Frazier & Rayner, 1982). A parallel interest in monitoring hand movements in Braille reading also has arisen recently (see Bertelson, Mousty & D'Alimonte, 1985; Mousty et Bertelson, 1985). A collection of chapters edited by Rayner (1983) provides us with a good overview of research on eye movements in reading.

Thus far, very few comparative studies of different orthographies have been undertaken with eye movement techniques. Yet, we already know that Hebrew-English bilinguals have opposite asymmetric functional visual fields (area of text from which useful information is extracted during a fixation) in reading Hebrew and English (Pollatsek, Bolozky, Well, & Rayner, 1981) and that Chinese-English bilinguals (living in California) read Chinese faster in horizontal than in vertical texts (Sun, Morita, & Stark, 1985).

CONCLUSION

Ever since the publication of *Language by ear and by eye* (Kavanagh & Mattingly, 1972) the interest for comparative studies in reading of different orthographies has been growing considerably. Some progress along this line has been made but major breakthroughs await more extended descriptions of how language is conveyed by speech, how it is conveyed by script, and how they are related. More specifically, we need the analysis of languages at the level of phonology, morphology, morphophonology, and syntax that is already provided by linguists, to be more extensively correlated with a fine-grained analysis of how the associated orthographies represent these different levels of description, which we still lack to a large degree.

Having these descriptions would allow us to assess which combinations are actually implemented in a two-dimensional space defined by different levels on the orthographical and phonological deepness-shallowness dimensions and how the reading process is affected by such variables. In the meantime, research has exploited the few cases in which a given language can be extensively represented in two different orthographies. Prominent examples of this approach concern the *kana-kanji* comparison in Japanese (e.g., Paradis et al, 1985), the pointed-unpointed comparison in Hebrew (e.g., Navon & Shimron, 1984) and the possibility of mixing two alphabets in Serbo-Croatian (e.g., Katz & Feldman, 1983). Along this line, one is certainly eager to find a group of Chinese people equally proficient in reading Chinese written in *pinyin* and in the logographic, traditional orthography, a possibility that is perhaps much less remote than in the past.

NOTES

[1] This definition of writing is still defective because it prevents considering the Braille tactile alphabet as a writing system. Lyons (1977, pp. 68-69) solved the problem by distinguishing between the medium in which the language is realized and the channel along which it is communicated. Writing is realized in the graphic medium that is usually communicated by visual marks along the visual channel, but a tactile message (change of channel of communication) isomorphic to the visual message still belongs to the graphic medium. Uncontracted Braille, which establishes a one-to-one correspondance between tactile patterns of dots and the letters of the written language, is therefore no less writing than the usual visible marks.

[2] I use the term grapheme to designate a class of graphs representing the same abstract written unit. For example, B, b, *b*, and 𝓫 are different graphs realizing the same grapheme. English and French are both written with 26 graphemes (disregarding diacritics and punctuation marks). This view is similar to that of

Venezky (1970c, pp. 47-49), but not to that of Sampson (1985; p. 25) who adopts a closer parallel between the graph-grapheme distinction and the phone-phoneme distinction. I find this latter position unsatisfactory as it obliges one to consider upper and lowercase letters as different graphemes because they play different, contrastive orthographic roles.

[3] Four diacritics are used to indicate tone in *pinyin*, the official alphabetic system used to transcribe Chinese. These diacritics, one to be placed above the vowel of each syllable, are ¯, ˊ, ˇ, and ˋ, corresponding to the high, rising, low, and falling tones, respectively.

[4] The number of entries in a dictionary is always indicated in terms of number of characters. Even though I lack the precise, explicit information, I take this to mean that only monomorphemic words are listed and that compound words never stand as entries. If compound words are indicated at all, they should appear under the heading of one of their constituent morphemes (e.g., *huǒchē*, meaning train, should be found either under *huǒ*, meaning fire, or under *chē*, meaning vehicle).

[5] The Korean alphabet is praised for being the only one in which some letter features portray the shape of the main articulators involved in the pronunciation of the corresponding sound. Korean is, therefore, the most subphonemic alphabet ever designed. This remarkable achievement of fifteenth century scholars is nevertheless immaterial to the main concern of this chapter because it is extremely unlikely that this characteristic of the script plays any functional role in the reading process.

[6] Chinese monomorphemic words should be extremely salient psychologically because of their coextensiveness with syllables that are themselves very clearly demarcated phonologically, the sets of possible initial and final consonants being almost disjoint (Sampson, 1985, p. 146). However, words are not always psychologically salient. For example, many Spanish common nouns of Arabic origin were generally not separated from the article "al" that should have been stripped from words such as "albañil", "alcade", "alfonbra", "almohada", and, last but not least, "álgebra".

[7] Notice, however, that exactly the ability tested here has been developed by Chinese scholars wanting to describe language sounds well before any alphabetic script was introduced into China (Kratochvíl, 1968, pp. 48-49). The pronunciation of a character is described either by comparison with one well known character having the same sound, or by comparison with two characters, one having the same initial consonantal value and the other the same final value (e.g., /lán/ could for instance be described by /luó/ and by /tán/, Kratochvíl, 1968, p. 49). Granted that the subjects used by Read, Zhang, Nie, and Ding (1984) probably spend little time musing about speech sounds, eventually acquiring the tested ability only if confronted with *pinyin*, the procedure just described is nevertheless commonly used in dictionaries.

[8] A somewhat related issue is the monogenesis hypothesis. Gelb (1963) argued that all writing systems may have a common ancestor ; namely, the Sumerian logography. Such an idea cannot be entertained unless the Maya script is classified as a semasiographic forerunner of writing. It seems, however, that there is a growing tendency to consider the Maya script to be highly logographic and even showing phonetization tendencies, though this latter possibility is much more controversial (Kelley, 1976). Even restricted to the Old World, the monogenesis hypothesis is probably doomed to stay highly speculative for ever. Although there is no proof to the contrary, Gelb's arguments for a common origin in the Near Eastern logographic scripts of both the Proto-Indic and the Chinese script are very tenuous at best.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

EFFECT OF PERIPHERAL VISUAL FIELD SIZE UPON EYE MOVEMENTS DURING JAPANESE TEXT PROCESSING[1]

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Saccadic eye movements were recorded during Japanese text processing and reading tasks in which logographic _kanji_ text and alphabet-like _kana_ text were employed. Subjects were asked to read the text on a CRT through a small restricted field of view in which the text is displayed and varied in size from 1 to 45 deg visual angle. The minimum effective visual field size was found to be approximately 20 and 10 deg for _kanji_- and _kana_-based processing, respectively. Further, for _kanji_-based processing a small number of large amplitude saccades were needed for optimized, conceptually-driven, text processing, whereas for _kana_-based processing a large number of short-range saccades were needed for optimized, data-driven, text processing.

INTRODUCTION

Lexical access during reading provides some interesting problems in relation with the eye movements underlying visual exploration strategies. Further, as Roman and Pavard (this volume) mentioned, very few data are available today on inter-language comparison topics and the differences between languages not only concern their semantics, syntax, and lexicon, but also the rules of concatenative structure and word formation. Specifically, the differences in lexical access and concatenative structure between Japanese and Indo-European languages appear evident.

Compared to other languages, Japanese has a unique structure. Investigations of language impairment in Japanese aphasic patients revealed fascinating features that are clearly different from those exhibited by aphasic patients who speak Indo-European languages (Sasanuma, 1975). _Kana_ and _kanji_ are two kinds of written symbols that are used in standard Japanese orthography. This creates some unique symptomatology in certain patients, such as the fact that use of one of the two kinds of written symbols tends to be selectively impaired (Kimura, 1934). Some examples of words and sentences in _kana_ and _kanji_ are shown in Figure 1.

Kana signs are alphabet-like phonetic symbols, or phonograms,

		Verbs	Nouns	Sentences
Japanese	kana	まなぶ	かれ、ことば	かれはことばをまなぶ
	kanji	学ぶ	彼、言葉	彼は言葉を学ぶ
English		learn	he,language	He learns language

Figure 1
Examples of Japanese words in *kanji* and *kana*, and equivalent sentences in Japanese and English

for syllables, whereas *kanji* character are essentially non-phonetic (non-sound-based) logographic symbols, or ideograms, representing lexical morphemes. In normal Japanese written sentences, mixed use of *kana* and *kanji* is the general rule. Although *kanji* can always be written in *kana* strings, lexical morphemes are usually written in *kanji*. However, all of the grammatical morphemes and various kinds of function words are written only in *kana* signs. There are more than 3000 standard *kanji* characters and two sets of 68 *kana* signs each, *hirakana* and *katakana*, which are equivalent to one another.

Although, each *kanji* character is composed of a complex pattern of sub-units, it gives information within each single character morpheme. This is in contrast with sound-based *kana*. Since normal Japanese text is written with combined use of *kana* and *kanji*, most Japanese have some difficulty in smooth text reading and processing under conditions in which sentences are written only in *kana* strings. This suggests that two kinds of symbols have different roles in text reading and processing.

It has been reported that the size of the peripheral visual field has a critical role in reading and searching (e.g., Levy-Schoen, 1977; Osaka, 1980; Rayner, Inhoff, Morrison, Slowiaczek & Bertera, 1981; O'Regan, 1984). And it is also well known that highly skilled "image" readers are usually readers who are highly trained in using clues that appear in the para-foveal and/or near-peripheral visual field (McConkie, Zola, Blanchard & Wolverton,1982).

Osaka (1984) measured the minimum effective visual field size for *kanji-kana* mixed Japanese text using a method of visual field restriction which was similar to the tube-method employed by Dolezal (1982). The level of text comprehension as well as difficulty were scaled and controlled. The data from 15 subjects revealed that the trade-off function between size of effective visual field vs. reading time is predicted by a log-linear model. The minimum effective visual field size was found to be between 14 to 26 deg in visual angle which corresponds to 10 to 20 text characters.

Since a general rule is that lexical morphemes are represented mainly in kanji while grammatical morphemes including various kinds of function words (such as verbs and adjectives) are represented in kana, the difficulty for reading a kana-only text is due to difficulty of visual exploration strategies. If the text is presented only with kana strings, a reader's para-foveal (or even peripheral) pre-processing ability (or top-down processing skill) will be deteriorated. Therefore, strategies of saccadic eye movements will concomitantly be changed.

My hypothesis here is that the kanji component will act as a facilitator for para-foveal pre-processing; Since kanji morphemes are composed of a complex pattern of sub-units which provide a quasi-picture-like gestalt structure, lexical access for kanji appears direct and fast as compared with kana strings. Furthermore, kanji is likely to be pre-attentively detected in para-fovea in terms of top-down processing due to its ideographic property. That is, in a written sentence, kanji ideograms work like stepping stones supporting the eye fixations in a stream of phonographically-based kana.

The present investigation aimed at a model of oculo-motor organization based on the difference between logographic (kanji) and alphabetical (kana) text processing systems.

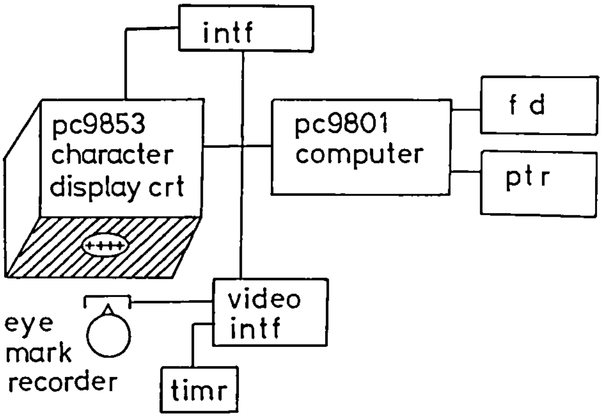


Figure 2
A computer-controlled measuring system.
Intf:interface, Fd:floppy disk, ptr: printer, Timr:Timing module.

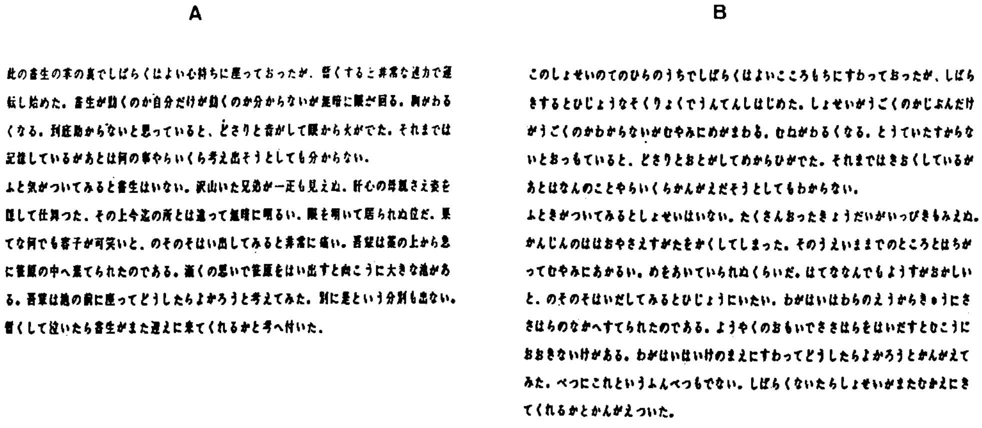
METHOD

Apparatus

The restriction of the field of view was done using a computer-controlled technique coupled with the NAC eye mark recorder. The subject's eye movements toward the fringe of the visible field initiated the appearance of the next coming field unit with text. The visible circular text field size, within which the text was presented, was changed from 1 to 45 deg visual angle in steps of 0.2 log units under the control of the computer: That is, 1, 2, 3, 4, 6, 10, 16, 25, and 45 deg in diameter. A block diagram of the measuring system and some examples of the field are shown in Figure 2. Japanese text was presented on a CRT screen with P33 phosphor and each character was defined in a 16 by 16 dot matrix. Font style employed here was Ming-font. Each line of characters subtended a visual angle of 45 deg.

Text material

Nine different sets of Japanese texts with kanji and kana (kanji-kana mixed mode) were employed. Each set contained 800 characters. One character subtended about 1 deg visual angle from 40 cm viewing distance. The original text was adopted from a well known Japanese novel "Wagahai wa neko dearu" written by Soseki Natsume. The equivalent kana-only versions of the same text were constructed (kana-only mode). Figure 3 shows examples of the texts employed: Left and right panels each indicate kanji-kana mixed mode and kana-only mode, respectively.



A

此の書生の掌の裏でしばらくはよい心持ちに座っておったが．暫くすると非常な速力で運転し始めた。書生が動くのか自分だけが動くのか分からないが無暗に眼が回る。胸がわるくなる。到底助からないと思っていると、どさりと音がして眼から火がでた。それまでは記憶しているがあとは何の事やらいくら考え出そうとしても分からない。

ふと気がついてみると書生はいない。沢山いた兄弟が一疋も見えぬ．肝心の母親さえ姿を隠して仕舞った．その上今迄の所とは違って無暗に明るい．眼を明いて居られぬ位だ．果てな何でも容子が可笑いと．のそのそはい出してみると非常に痛い。吾輩は藁の上から急に笹原の中へ棄てられたのである。漸くの思いで笹原をはい出すと向こうに大きな池がある。吾輩は池の前に座ってどうしたらよかろうと考えてみた。別に是という分別も出ない。暫くして泣いたら書生がまた迎えに来てくれるかと考へ付いた。

B

このしょせいのてのひらのうちでしばらくはよいこころもちにすわっておったが、しばらくするとひじょうなそくりょくでうんてんしはじめた。しょせいがうごくのかじぶんだけがうごくのかわからないがむやみにめがまわる。むねがわるくなる。とうていたすからないとおっもていると．どさりとおとがしてめからひがでた。それまではきおくしているがあとはなんのことやらいくらかんがえだそうとしてもわからない。

ふときがついてみるとしょせいはいない。たくさんおったきょうだいがいっぴきもみえぬ。かんじんのははおやさえすがたをかくしてしまった。そのうえいままでのところとはちがってむやみにあかるい。めをあいていられぬくらいだ。はてななんでもようすがおかしいと．のそのそはいだしてみるとひじょうにいたい。わがはいはわらのうえからきゅうにささはらのなかへすてられたのである。ようやくのおもいでささはらをはいだすとむこうにおおきないけがある。わがはいはいけのまえにすわってどうしたらよかろうとかんがえてみた。べつにこれというふんべつもでない。しばらくないたらしょせいがまたむかえにきてくれるかとかんがえついた。

Figure 3
Examples of the Japanese texts employed during experiments. Panel A:Kanji-kana-mixed mode. Panel B:kana-only mode (After "Wagahai wa neko dearu" by Soseki Natsume

Procedure

After a 10 min calibration period for saccade measurement, the subject was asked to read silently the text on a CRT screen as accurately as possible through a given small circular visual field which varied in size from 45 to 1 deg visual angle.

Saccadic eye movements and reading time were recorded. Subjects received kanji-kana mixed session and kana-only session in a random order. After each experimental session, the subject was asked to rate the difficulty (5 point scale; 1 for very easy and 5 for very difficult) of the task, and was asked to answer 10 questions concerning the story of the text just read. The percentage of correct answers was taken as a measure of text comprehension for both kanji-kana and kana-only text conditions and for each field size.

Subjects

16 students who had normal or corrected-to-normal vision were employed as subjects. They were selected from about 50 students in order to equalize reading ability on the basis of a language skill test.

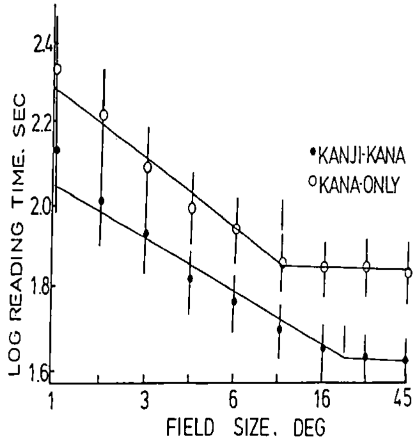


Figure 4
Log reading time (time required for complete reading) as a function of visual field for kanji-based and kana-based group. Vertical bar indicates ±1 SD unit

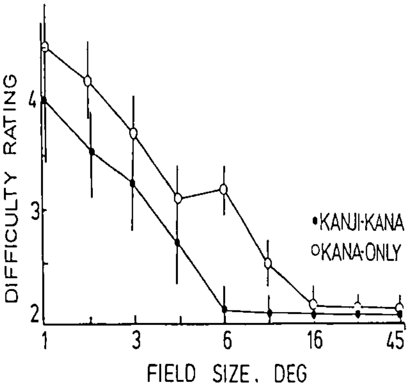


Figure 5
Difficulty scale as a function of field size for kanji-based and kana-based group (scale value: 1 for very easy and 5 for very difficult). Vertical bar indicates ±1 SD unit

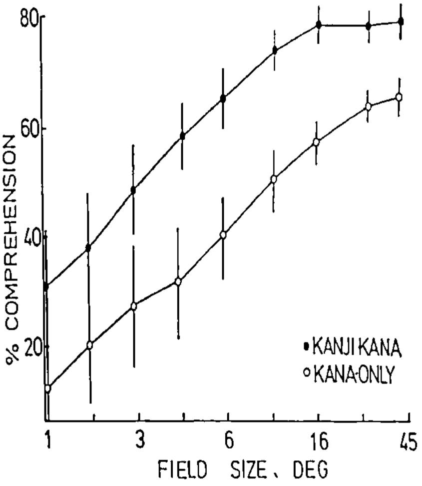


Figure 6
Percentage of correct responses as a function of field size for *kanji-kana* and *kana* group. Vertical bar indicates ±1 SD unit

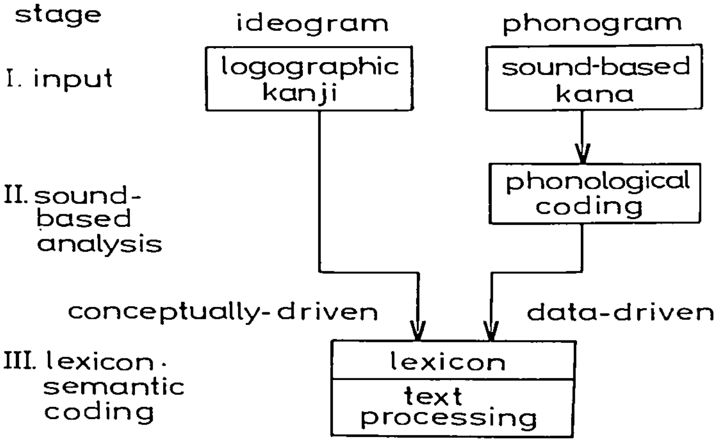


Figure 7
A model of *kanji* and *kana* text processing in terms of lexical access

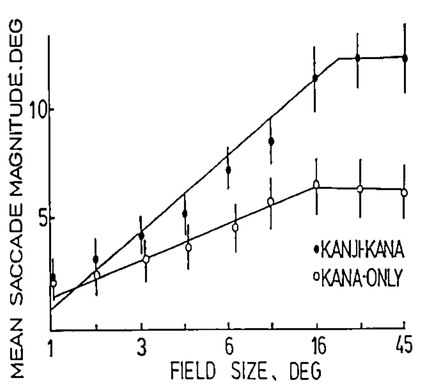


Figure 8
Mean saccade magnitude as a function of field size for kanji-kana and kana-only groups. Vertical bar indicates ±1 SD unit

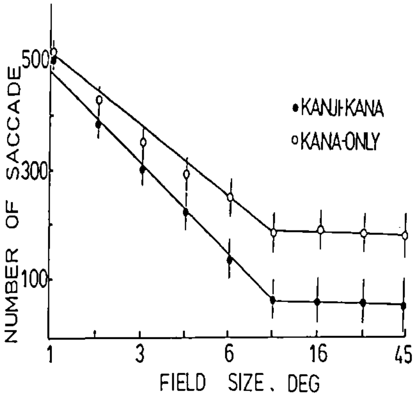


Figure 9
Number of saccades as a function of field size for kanji-kana and kana-only groups

RESULTS AND DISCUSSION

Figure 4 shows log reading time as a function of visual field size. Each data point plots mean and ±1 SD based on 8 measures. As visual field size increases from 1 to 45 deg, the time required for reading decreases. However, the reading time for the kanji-kana group was significantly faster than that for the kana-only group at all field sizes.

Figures 5 and 6 show difficulty ratings and comprehension percentages as a function of field size. These Figures suggest that as field size decreased, reading difficulty increased and therefore the percentage of correct answers decreased. In both measures the kanji-kana group showed better performance as compared with the kana-only group ($p < .05$). It appears that kanji-kana mixed text is more easily processed than kana-only text. Figure 4 suggests that reading time is almost independent of field sizes larger than 20 deg for the kanji-kana mode, while this occurred at 10 deg for the kana-only mode. This can be seen from the eye-fitted lines in Figure 4: at the break point, reading time levelled off. This suggests that the minimum effective visual field size for kanji-kana mixed text and kana-only text will be approximately 20 and 10 deg, respectively.

Figure 7 indicates a model of text processing for the two kinds of written text symbols. Kanji input can directly reach the lexical level at stage III without any pre-processing due to its logographic properties. On the other hand, kana input must be phonologically coded at stage II before reaching stage III (the lexicon) because of its sound-based coding properties. It should be noted that lexical access appears easy for the kanji-based component as compared with the kana-based component. The time required for reading is predicted to be faster for kanji-based text than kana-based text. This is what we obtained in Figure 4.

Figure 8 shows mean amplitude of saccadic eye movements as a function of field size. As the field size increased, the magnitude of saccades gradually increased up to field sizes of 20 deg and 16 deg for the kanji-kana and kana-only groups, respectively. Figure 9 indicates number of saccades as a function of field size. As field size increased the number of saccades decreased up to about 10 deg field size for both groups. These data suggest that as field size increases, magnitude increases and number of saccades decreases. This indicates that kanji characters facilitate and increase the speed of semantic processing. This can be predicted from the model: The fact is that the minimum effective field for kanji-kana mixed text is about 20 deg. This would permit that a small number of saccades with large amplitudes between 10 and 15 deg were needed for optimized text processing. This type of processing can be called "conceptually-driven" processing having a "top-down" processing structure. The fact that kana-only text needs only 10 deg for minimum effective visual field suggests that many short-range saccades were needed for optimized text processing. This type of processing can be called "data-driven" or "bottom-up" processing. The merit of kanji-kana mixed text processing over kana-only processing could be explained in terms of differences of such a conceptually- and data-driven processing style coupled with minimum effective peripheral visual field size.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

A COMPARATIVE STUDY :
HOW WE READ IN ARABIC AND FRENCH

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In these experiments, we compared reading processes in arabic and in french. We observed that texts are read at the same speed in the two languages and that oculomotor activity is related to the morphological structure of words. Arabic text reading processes seem impaired when introducing vowels. We conclude that lexical access of non concatenative languages like arabic or hebrew may be very different from access in concatenative ones like french or english.

INTRODUCTION

Interlanguage research provides an experimental approach to many psycholinguistic problems, as it offers natural variations impossible to obtain in the laboratory when working on one language only. For instance, it is not possible to vary the number of morphemes in a word without at the same time modifying the graphic characteristics of the word. Furthermore it is very difficult to investigate the respective effects of consonants and vowels in the mental representation of words, since in concatenative languages both consonants and vowels are closely related to graphic structure.

On these two points, comparison between french and arabic is interesting. These two languages have different morpholexical structures : while french has a concatenative morphological structure (morphemes follow one another linearly), arabic has a non concatenative one based on the notion of root. The arabic vocabulary is built on roots generally composed of three consonants (Figure 1.).

KATABA	He wrote
KATTABA	He caused to write
KAATABA	He corresponded
TAKAATABAA	They kept up a correspondance
KITAABUN	Book (noun)

Figure 1. - Non exhaustive list of words morphologically related to the root **KTB**.

In the experiment to be presented, we will consider visual scanning strategies in relation with morphological structure. French and arabic were choosen because they differ strongly in their morphological structure though they have the same mean word length.

There are few comparative experimental results about reading of concatenative and non concatenative languages. The first research using oculomotor recording was carried out by Gray in 1956 on fourteen languages with University of Chicago students. The main conclusion emerging from his work was that characteristics of oculomotor exploration during reading appeared to be universal. More recently, Pollatsek, Bolozki, Well and Rayner (1981) carried out a comparative study between Hebrew and English using bilingual hebrew subjects. They compared oculomotor recordings and found similar reading speed in English and Hebrew but with longer fixation durations and smaller saccade sizes in hebrew. The authors accounted for their finding (the problem of oculomotor adaptation) in terms of informational density of words.

In the subsequent experiment we compared oculomotor patterns during the reading of french, non vowelised and vowelised arabic texts.

EXPERIMENT 1 : **Comparative analysis of visual scanning in arabic and french**

In arabic countries, vowels are not indicated in the script used in most publications. Therefore an arabic text contains fewer letters than a french or english one. But in arabic, words have, on the average, the same number of letters.

In the first experiment we tried to analyse the oculomotor regulation mechanisms in relation to informational density of words. As french and arabic texts used in this experiment are semanticaly equivalent, the mean informational density of words is only in relation with the number of words used in each text.

Method

Subjects

Our experimental sample consisted of two groups of subjects :
one french speaking group and the other arabic speaking. All subjects were selected on the basis of their schooling language. This decision is based on the fact that the arabic language is marked by differences between its written and spoken forms.

The french speaking group consisted of 12 algerian university students for whom french was the only schooling language ; the arabic speaking group consisted of 12 arab university students of different nationalities (i.e., algerians, egyptians, lebanese, palestinians, syrians...) for whom arabic was the only schooling language. They all had good sight.

Linguistic material

We used 4 short stories. In order to avoid differences in semantic content (the referent), two stories where translated from arabic into french and the remaining two from french into arabic.

The four texts contained approximately the same number of words (about 140 in french and 95 in arabic) and they contained the action at the beginning so as to facilitate the evaluation of comprehension.

Procedure

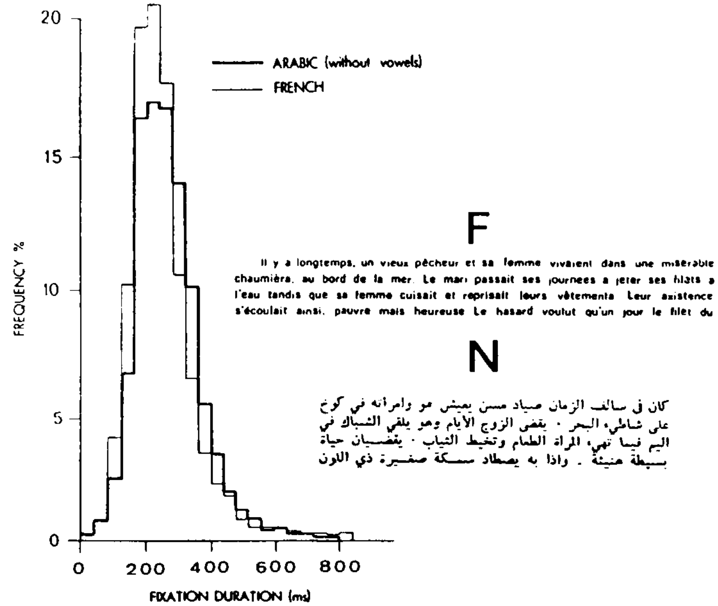
Subjects were seated 40 cm from the text ; there were about four characters per degree of visual angle ; a bite-board and head rest prevented any head movement during reading sessions. An eye-view monitor system (model 200, Applied Science Laboratories) was used to record eye-movements.

Two additional texts, one in arabic and one in french, were also used to reject subjects displaying either sight problems or a lack of mastery over one language or the other.

Following the reading sessions, subjects were asked to verbally summarise the stories. Only the results of those producing a correct summary, or appropriate answers on the stories were considered for final statistical analysis. Each of the two groups was presented with four different texts. That is, the four stories in arabic for the arabic-speaking group, and the same four stories in french for the french-speaking group.

Results and discussion

For arabic and french texts the fixation durations were not significantly different ($t=1.32$ $p>.20$) although we observed an increase of 15 msec in arabic (Figure 2).



Il y a longtemps, un vieux pêcheur et sa femme vivaient dans une misérable chaumière, au bord de la mer. Le mari passait ses journées à jeter ses filets à l'eau tandis que sa femme cuisait et reprisait leurs vêtements. Leur existence s'écoulait ainsi, pauvre mais heureuse. Le hasard voulut qu'un jour le filet du

كان في سالف الزمان صياد مسن يعيش هو وامرأته في كوخ
على شاطئ البحر . يقضي الزوج الأيام وهو يلقي الشباك في
اليم فيما تهيء المراة الطعام وتخيط الثياب . يقضيان حياة
بسيطة هنيئة . واذا به يصطاد سمكة صغيرة ذي اللون

Figure 2. - Distribution of fixation durations when reading arabic (without vowels : N) and french (F) texts.

The mean reading time did not differ between the arabic and french texts (t=1,12 p>.20). We found the same mean total number of fixations (125) for arabic and french texts.

However, gaze duration per word was significantly different (t=6.2 p<.001), being longer in arabic (342 msec) than in french (215 msec), (Figure 3).

	FIXATION DURATION	GAZE DURATION	NUMBER OF WORDS PER LINE	TOTAL TEXT READING TIME
ARABIC	261 msec	342 msec	10	21,2 sec
FRENCH	246 msec	215 msec	15	23 sec
RATIO A/F		1.59	10/15	

Figure 3. - Table of eye movement's main characteristics during reading french and arabic (non vowelized) texts.

In our view, the most important finding in this experiment is that the ratio of french to arabic gaze durations is similar to the ratio of the number of words in the french and arabic versions of the texts and equal to 1.5. This means that gaze durations per word correlates negatively with the number of words in the text. Thus oculomotor regulation during reading seems to depend on lexical facts : in arabic the reader chooses to make more fixations per word, thus reducing the amplitude of his eye movements rather than increasing the duration of fixations. As arabic and french words have the same length (4.4 letters on average), this effect cannot be explained in terms of gross graphic differences.

However, if graphic factors (and hence perceptual processing) are not involved in the increase of gaze duration per word, a further issue is raised concerning cognitive factors. Indeed, as we have seen, the concatenative structure and affixes result in the arabic text consisting of fewer words than its french counterpart. That is why we used, in the absence of a morphemic theory covering both languages, as a measure of informational density, the ratio of the number of words in the two languages. However it should be stated that the arabic language, despite its specificity, is nevertheless an alphabetical language like french or english. Further, if arabic words have, on average, the same number of letters as french words, this is due solely to the absence of vowels. We therefore cannot be certain, on the basis of this first experiment, that it is the informational density rather than lack of vowels which explains the increase of gaze duration per word. For instance, we can hypothesise that the increase in gaze duration per word would be the consequence of the cognitive operations necessary for inferring the vowels. This hypothesis can be experimentally examined since the arabic language can be written with vowels. This is done during the first schooling years or for any literary novel of considerable importance. Experiment 2 was designed and carried out to evaluate this specific effect of vowels on cognitive processes.

EXPERIMENT 2 : Comparison between vowelized and non-vowelized arabic texts.

Method

Subjects

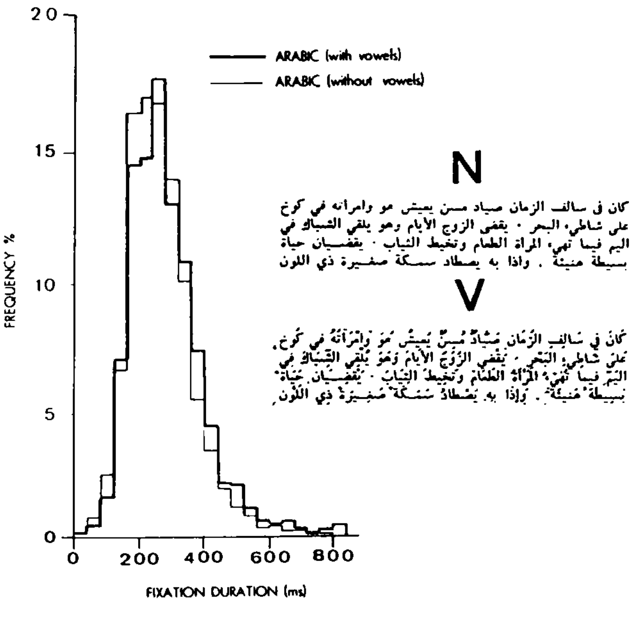
12 arab university students participated in the experiment.

Linguistic material

The arabic texts used in the first experiment were vowelized.

Results and discussion

We observed that vowels signicantly reduce reading speed ($t=7.61$ $p<.001$). At the same time, vowels increase the number of fixations significantly ($t=4.99$ $p<.001$)and they also increase fixation durations ($t=6.8$ $p<.001$). The gaze duration is 75 ms longer in vowelized texts than in non-vowelized ones (figure 4).



كان ف سالف الزمان صياد مسن يعيش مو وامراته في كوخ
على شاطئ البحر . يقضي الزوج الأيام وهو يلقي الشباك في
اليم فيما تهيء المراة الطعام وتخيط الثياب . يقضيان حياة
بسيطة هنية . واذا به يصطاد سمكة صغيرة ذي اللون

كَانَ فِي سَالِفِ الزَّمَانِ صَيَّادٌ مُسِنٌّ يَعِيشُ مُو وَامْرَأَتُهُ فِي كُوخٍ،
عَلَى شَاطِئِ الْبَحْرِ . يَقْضِي الزَّوْجُ الأَيَّامَ وَهُوَ يُلْقِي الشِّبَاكَ فِي
الْيَمِّ فِيمَا تُهَيِّءُ الْمَرْأَةُ الطَّعَامَ وَتَخِيطُ الثِّيَابَ . يَقْضِيَانِ حَيَاةً
بَسِيطَةً هَنِيئَةً . وَإِذَا بِهِ يَصْطَادُ سَمَكَةً صَغِيرَةً ذِي اللَّوْنِ،

Figure 4. - Distribution of fixation durations during reading of vowelized (V) or non vowelized (N) arabic texts.

We therefore hypothesise that the control of visual exploration during reading is regulated at the lexical level. If the reader must process a large amount of information at the word level, he increases gaze duration by word, not by lengthening fixation durations, but by making one or several additional fixations. The difference observed between reading arabic and french cannot be attributed to graphic factors because, in non vowelised arabic texts, the words have on average the same number of characters as in french. This difference also cannot be attributed to operations of vowel inference since when texts are vowelised (experiment 2), reading processes become disturbed.

Thus, we explained this difference in terms of informational density. The arabic reader extracts more information for every word because for the same referent the arabic text has fewer words than the french one.

Furthermore, the effect of adding vowels is surprising. We must hypothesize that the presence of vowels, either constitutes a kind of perceptual noise (due for example to masking effect between lines), or induces an information processing process (syntaxic and semantic) carried by the vocalic morpheme. In either case, however, vowels delay access to the meaning of the text.

EXPERIMENT 3 : Lexical access of arabic words with or without vowels.

As these two experiments seem to suggest that the arabic reader acquires the meaning of words from consonants only, we attempted to investigate the possibility of the existence of a consonantal lexical representation.

The following are two hypothetical models of lexical access : one involves a syllabic representation and another a consonantal representation.

- in the first case, the vocalic morpheme is inferred in order to build up a syllabic representation and to access the mental lexicon.

- in the second case, the visual analysis of the root provides a direct access to the mental representation.

From the consonantal root K.T.B., the reader may directly access a consonantal representation, but in the case of a syllabic one, the reader will have to :

- either take into account vowels when written.
- or infer these vowels when not written.

In either case this processing will lead to a greater cognitive load.

Evidence in favour of direct access to consonantal representation is both empirical and theoretical.

1. arabic writing is consonantal in most if not in all cases,

2. arabic dictionaries are based on roots i.e., word search is governed by root search,

3. in most arabic dialects, vowels are not pronounced. They just tend to facilitate vocalisation (Pellat, 1970),

4. morphological analysis of verbal forms shows that, whatever the vocalic morpheme used, the sequence of the root morpheme's consonants remains stable (Mc Carty, 1981),

5. vowels in hebrew have little effect on response latency (Koriat, 1985).

In order to investigate this point we carried out an experiment using a lexical decision task (word/non-word).

Method

Subjects

40 arabic speaking students from the Université des Sciences et de la Technologie Houari Boumediene of Algiers took part in these experiments as volunteers. Their only schooling language was arabic. Subjects were assigned to one of four experimental conditions - there were 10 subjects in each condition.

Linguistic material (See Appendix)

8 trilitary roots (3 consonants) were used in four experimental conditions. The roots allow several acceptable vocalisations. In these experiments we used only the more common forms, one being verbal, and one nominal. Non-words consisted of inappropriate associations of consonants or vowels.

Experimental procedure

The linguistic material was presented on a V.D.U. Subjects were required to perform a double lexical decision task (word and non- word) by pressing on one of the two buttons placed under their more skilled hand. They were instructed to press with their forefinger on knob 1 whenever a stimulus was identified as a word, and to press with the second finger on button 0 when it was a non-word.

In conditions C1 and C2, subjects were asked to perform a lexical decision task only on roots which were either non vowelised (condition C1) or vowelised (condition C2).

In conditions C3 and C4, subjects were asked to perform a lexical decision task on the whole set (that is root + vowels). Accordingly :

- condition C3 : vowels will give a nominal meaning to the word.
- condition C4 : vowels will give a verbal meaning to the word.

Results and discussion

The main result of this experiment is that the presence of vowels significantly increased lexical decision latency (Figure 5). Even if lexical decision concerned the root only (condition C2), vowels delayed the response by 300 msec, this difference being highly significant ($t = 4.4$; $df = 9$; $p < .001$).

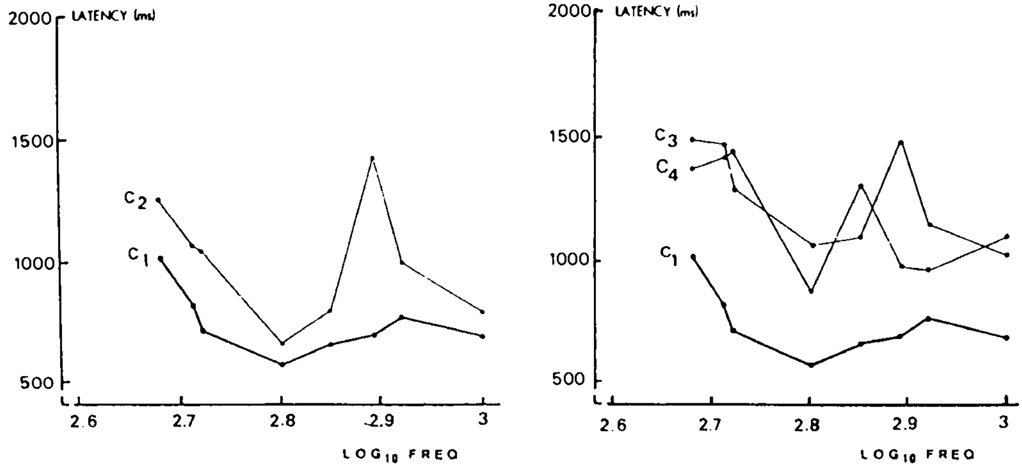


Figure 5 - Latency for arabic words in relation to their estimated frequency (Log 10 freq).
C1 - Decision on roots without vowels.
C2 - Decision on roots with vowels.
C3 and C4 - Decision on both roots and vowels (normal vowelization).

In conditions C3 and C4, subjects were asked to process both root and vowels, which resulted in a drastic increase of latency (500 msec). This effect can be compared to experiment 2 where subjects were asked to read a well-structured text. In such conditions, the only influence of vowels is to increase the gaze duration by 75 msec.

Two hypotheses can be put forward :

1. Linguistic material was not presented on the same medium in the two experiments. Reading was on paper while lexical decision was on a VDU screen. This latter medium is of lower quality than the first, as vowels were less visible and the consonant design less precise on the screen.

This difficulty might explain the particularly long delay we observed.

2. The lexical decision task may be more difficult in arabic than in french. As we already noted, arabic roots only contain a limited amount of information compared to french words, so readers must use more contextual information in order to access arabic words.

CONCLUSION

The purpose of this study was to compare reading processes in arabic and french and to explain the differences, if they exist, in terms of linguistic structure. In the first experiment, we compared visual strategies during reading of french and arabic texts that were semantically equivalent.

We observed that french and non-vowelized arabic texts are read at the same speed : thus, arabic readers seem to use cognitive strategies in order to infer vocalic information from the context.

We also observed that oculomotor activity is different in the two languages. Contrary to other results obtained in hebrew (Pollatsek et al., 1981), we show that differences in scanning patterns concern gaze duration and are not due to fixation duration : gaze durations for arabic words are 1.5 times longer than in french and this is exactly the same ratio as for the number of words per line in the two languages.

Simultaneously, we observed that the regulation of oculomotor activity during arabic text reading is modified when introducing vowels : both fixation duration and gaze duration are much longer.

Are the mechanisms of lexical access different in concatenative (like the french and english) and non concatenative languages (like arab or hebrew) ?

We put forward the hypothesis that arabic words may be accessed directly from their consonant root without written (vowelized texts) or inferred (non-vowelized texts) vowels. This hypothesis seems to concur with other results obtained by Courrieu and Do (this volume) who used a paradigm of letter masking. In french, the masking effect is correlated with the position of the masked letter in the word: if it is placed at the beginning of the word, the effect is stronger than at the middle or at the end. This result is interpreted by the authors to be in favor of a word processing model based on a serial analysis of letters. But this effect is not observed in arabic when short vowels are concerned, which would mean that vowels, when present, are not examined as they come along, but rather afterwards, after the scanning of the root. This is in favor of a lexical access model based on a separate analysis of consonantic and vocalic morphemes, but does not specify whether vocalic information is accessed during reading.

An experiment on reading of ambiguous sentences (Roman and Pavard, 1985) may constitute some information about this question. Ambiguous sentences were read orally or silently. The ambiguous verb was not vowelized and was placed at the beginning of the sentence so that subjects could not determine its case (active or passive).

Results show that readers make an hypothesis on the case in order to interpret subsequent elements of the sentence. Therefore, this experiment explains why readers must infer the abstract information that is not carried by the root (here the case), but raises a new problem : how do they access such information ? Is it necessary to infer the vocalic morpheme associated with the lexical information (here the case) or is this information coded in a abstract way independantly of the vocalic morpheme?

Further experiments will answer these questions nevertheless it is clear that strategies of visual scanning of words are very different from one language to the other, specially if their structures do not share the same morphological system (as in semitic and indo-european languages).

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APPENDIX

1. The eight stimuli :

فرح عذر
شرف شكر
حسد زرى
ضرب بصر

2. Example of nominal vowelisation : زَرْىٌ

and verbal vowelisation : زَرَىَ

3. Example of non-word (inappropriate combination of consonants) : سكش

4. Example of non-word (inappropriate vocalic pattern): نَضْلٌ

EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

PARAFOVEAL PREPROCESSING IN BILINGUALS

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Using a bilingual lexical decision task, we investigated subjects' ability to process parafoveally presented words in their first and second language, and whether or not this ability depended upon expectancy. The sequence of events was as follows : a prime word was presented foveally, followed by a parafoveal stimulus, followed by a foveal target word. Results showed that, in both languages, the prior parafoveal presentation of foveal targets improved performance. At short delays between prime and parafoveal words, facilitation was observed only when the two words were related. At longer delays however, benefits were accrued from parafoveal words independently of primes.

INTRODUCTION

Numerous recent studies have shown that information can be gathered from the parafoveal area of vision. It has been shown for example that, in experimental situations simulating normal reading, information may be picked up as far as 12 character spaces to the right of fixation (McConkie and Rayner, 1975; Rayner, 1975). The prior presentation of a word in parafoveal vision has also been shown to reduce the time needed to name the word when later presented in foveal vision (Rayner, 1978; Rayner, McConkie and Ehrlich, 1978; Rayner, McConkie and Zola, 1980; McClelland and O'Regan, 1981).

However, though the processing of parafoveal information seems to be rather well established (though see McConkie, Zola, Blanchard and Wolverton, 1982), what exactly is processed, and under what conditions remains an open question.

One question that has arisen is whether the efficient use of information presented in parafoveal vision is contingent upon expectancy. On the one hand, it is argued that some abstract code about the first letters of a stimulus presented up to 3 degrees of visual angle from fixation is obtained, quite independently of subjects' expectations (Rayner, 1978; Rayner et al. 1978; Rayner et al., 1980). On the other hand, various authors have put forward the notion that, if the parafoveal stimulus is not identical to the foveal target word, some prior expectation concerning the identity of the foveal word is indeed necessary for naming facilitation to be produced by the prior presentation of this word in parafoveal vision (McClelland and O'Regan, 1981; Paap and Newsome, 1981).

While there may be debate as to whether or not the efficient use of parafoveal information is actually dependent upon prior expectancy, it is concurred that a preceding context presented in foveal vision can indeed interact with the processing of parafoveal stimuli. This was clearly demonstrated in one experiment reported by McClelland and O'Regan (1981) in which, prior to the presentation of the parafoveal stimulus, a sentence was presented that permitted strong, weak or no expectations about the identity of the target word to be presented in foveal vision. The parafoveal stimuli themselves were either identical to the target, visually similar or neutral. The facilitation produced by parafoveal stimuli was greater, the stronger the context. Moreover, whereas the visually similar parafoveal stimuli did not in themselves facilitate performance, they did when preceded by strong or by weak contexts. In a recent study by Inhoff (1982), where a foveal word and a parafoveal word were simultaneously presented, the results of three experiments showed that parafoveal words were correctly reported more often when they were semantically related to the foveal words than when no such relationship existed.

The results of these two studies unequivocally demonstrate that a semantic context presented in foveal vision can indeed play a role in the effective use of perceptual information presented parafoveally. In the present experiment, we wished to further explore this phenomenon. Rather than impoverish the visual resemblance between the parafoveal stimulus and the foveal target word, we played upon the subject's ability to rapidly analyze the perceptual characterisitics of words.

One way of accomplishing this is to use subjects whose decoding skills are known, or believed, to be somewhat laborious. Such is the case, for example, of beginning bilinguals concerning their skills in their second language. It has been found in bilinguals, and especially in less-skilled bilinguals, that word recognition, as well as reading rate, is slower in the second language as compared to the first (Favreau, Komoda and Segalowitz, 1980; Favreau and Segalowitz, 1983). This pattern of results indeed closely resembles that found in skilled and less-skilled readers, where the latter show longer response times in word recognition tasks than do skilled readers (Perfetti and Hogaboam, 1975; Perfetti, Finger and Hogaboam, 1978). This difference in word recognition and reading rate between skilled and less-skilled readers, as well as between the first and second language of bilinguals, is generally accounted for in terms of differences in bottom-up processing abilities. In accordance with this idea, there appears to be some evidence that bilinguals' slower word recognition rate in their second as compared to first language is linked to a lesser ability to take advantage of orthographic redundancies (Favreau et al., 1980). Prior to the experiment, we tested our subject pool, and found that they indeed showed lesser sensitivity to letter strings composed of digrams frequent in their second language (French) than to letter strings comprising digrams frequent in their first language (English).

The aim of our experiment was twofold. First, we tested whether our unskilled bilinguals could benefit from the prior parafoveal presentation of a foveal target word, both when the word was presented in their first, and in their second, weaker language. Secondly, we tested to what extent the processing of parafoveal stimuli was dependent upon the prior presentation of a semantically related prime word presented in foveal vision, this latter being in either the first or the second language and corresponding or not to the language of the target stimulus. The conditions were such that subjects could either strategically employ or, to the contrary, not rely upon the prime word to predict target words.

The procedure and temporal parameters employed were much like those used by McClelland and O'Regan (1981) although a few major differences should be noted. First, we employed a lexical decision task rather than a naming task. Secondly, a word, not a sentence, was used as prime, and the length of time that subjects were given to read this word was experimentally limited. Thirdly, subjects were not informed of the presence of parafoveal stimuli. As concerns the presentation of parafoveal and foveal stimuli however, we followed the same procedure as outlined by these authors.

METHOD

Subjects. 48 students participated on a volunteer basis. All were native speakers of English, had lived in France for 6 to 9 months, and were completing university classes in French.

Stimuli. Target letter strings were 182 four and five letter words, taken from French and English. Half of these were transformed into nonwords by changing one letter. Of the remaining half, 48 served as "context words", and 48 as test words. The latter were selected along two criteria: (1) they had one relatively strong antonym (Webster, 1951; Boussinot, 1981), and (2) their spelling was dissimilar in the two languages. An additional 40 letter strings were used for practice.

Test words were preceded by one of three types of prime words, ranging between 3 and 7 letters in length. Semantically related primes were the antonyms corresponding to the test word (e.g. hot-cold). Unrelated primes were words that had logical antonyms, but which were not that of any of the test words (e.g. near-cold). Neutral primes (hereafter called "number-primes") were spelled-out numbers (e.g. five-cold). Numbers were used as neutral primes given that they present the advantage of being both semantically neutral and that logically they demand as much perceptual processing as other words, which may not be true for a string of Xs (see Jonides and Mack, 1984).

The type of context word as well as the type of preceding prime word differed according to the experimental condition they were used in. In one condition, all context words had logical antonyms, and the primes were either number-primes or the corresponding antonym (e.g. smile-frown). In the other condition, the context words were common nouns not possessing logical antonyms, the primes being either number-primes or unrelated common nouns (e.g. butter-book).

The languages of presentation of prime words and of test words were factorially combined to give rise to four conditions of language presentation. The same was done for context words.

Nonwords were preceded by prime words which fell into three equal classes: (1) words that had antonyms, (2) common nouns which did not have logical antonyms, (3) number-primes.

Apparatus. The experiment was controlled by an Apple IIe computer, with stimuli being presented in uppercase on the video screen. Characters were defined in a 7 X 7 dot matrix, with two columns of dots being reserved for blank space between characters. The size of the matrix was equal to 5 X 5 mm. Prime words were presented foveally, with the third letter of the word being positioned at the initial fixation point. Parafoveal stimuli (hereafter called "previews") were presented beginning 7 character spaces to the right or ending 7 character spaces to the left of fixation, and corresponded to 2 of visual angle. Target letter strings were presented in the same location as previews.

Subjects were seated at a distance of 1 meter from the video screen, with their chin in a chin rest. They were to make a lexical decison (manually) about the target letter string, and responded positively with their dominant hand. Responses and response times were recorded.

Design. Each subject participated in two "delay-context" conditions. In each condition, there was a total of 96 trials (24 test word, 24 context word, 48 nonword). The two conditions differed however in respect to the type of context words presented, and in respect to the stimulus onset asynchrony (SOA) between the prime word and the preview. In the "long-SOA-strong-context" condition, the related context words were presented, and the SOA was 740 msec. In this condition, subjects were led to expect a relationship between the prime and the target word, and the SOA was sufficiently long for subjects to engage in strategic processing (Posner and Snyder, 1975). In the "short-SOA-weak-context" condition, the non-related context words were presented, and the SOA was 240 msec. In this condition, the low proportion of related trials did not enable subjects to predict target words, and the SOA was short enough to preclude the intervention of attentional processes. The 20 practice trials preceding each condition conformed to these conditions.

The same two preview conditions were used in both experimental conditions. The preview was either identical to the target letter string (50% of trials), or a string of 5 uppercase Xs (50% of trials). The location of presentation of preview stimuli was determined by the type of target stimulus they preceded. All test targets and their corresponding previews were presented to the right of fixation. This was done so as to have the test targets presented in the best viewing position, since in many studies a right visual field advantage has been shown. All context targets and their previews were presented to the left of fixation. Half of the nonword targets and their previews were presented to the left of fixation, and half were presented to the right.

Each subject received a different assignment of test words to conditions, as determined by a latin-square. The order of presentation of all possible types of trials was random and randomly varied across subjects.

Procedure. Subjects were tested individually. The main experiment was divided into two blocks, in accordance with the delay-context condition. Each block commenced with a series of practice trials, and the order of presentation of the two blocks was counterbalanced over subjects.

Each trial began with the presentation of a fixation point, followed by a warning tone, followed by the presentation of a prime word. The prime word remained on for 140 msec, and was followed by a new fixation point which remained on for either 100 msec or 600 msec in accordance with the experimental condition. A preview stimulus was then presented to the left or right of the fixation point at random. The preview remained on for 100 msec, and was followed by a blank interval of 100 msec. A target letter string was then presented in the same position as the preview stimulus, and remained on the screen until the subject had made a lexical decision.

Subjects were instructed as follows. They were to fixate the initial fixation point, read the prime word to themselves, and then fixate the second fixation point until they saw the target stimulus appear, at which time they were to shift their gaze, look at the stimulus, and make a lexical decision. Subjects were not informed of the presence of preview stimuli.

RESULTS and DISCUSSION

Mean response times and percentages of correct responses to test words as a function of prime type, prime language, target language, preview type, and delay-context condition are shown in Table 1. Separate analyses were carried out on response time and response accuracy data. Results of these analyses showed that facilitation effects bore essentially upon response time, whereas interference effects bore essentially upon response accuracy. Response times to test words preceded by related antonym, neutral number and unrelated antonym primes were 609, 636 and 641 msec respectively. The main effect of prime type can be explained by the facilitation created by related primes ($F(1,92) = 7.21$, $p < .01$), with no significant residual variance ($F < 1$). Concerning response accuracy, related, neutral and unrelated primes gave rise to 92%, 91% and 88% correct responses respectively. Here, the main effect of prime type was explained by the interference effect created by unrelated primes (F(1,92) = 4.55, p <.04) with no significant residual variance (F <1).

When the effects observed in the analysis of response times were considered in relation to those observed in the analysis of response accuracy, it moreover became apparent that certain interactions including unrelated antonym prime conditions were explained in terms of speed-accuracy trade off. The fact that the structure of our experimental design precluded the exclusion of response time data corresponding to incorrect responses led us to exclude the unrelated prime conditions from response time analyses. We chose rather to study the effects of facilitation on response time, and those of interference on response accuracy.

Response Accuracy

A 2 (prime type: unrelated antonym or neutral number) by 2 (prime language) by 2 (target language) by 2 (preview type) by 2 (delay-context) by 2 (order of presentation) analysis of variance was performed on response accuracy data. There were significant main effects of target language (F(1,46) = 35.25, p <.001) and of delay-context condition (F(1,46) = 5.54, p <.02). The first effect merely shows that subjects responded with greater accuracy to test words presented in their first language (95% and 84% for English and French respecitively). Of much greater interest is the different pattern of responses observed in the two delay-context conditions. Subjects responded with greater accuracy in the short-SOA-weak-context condition than in the long-SOA-strong-context condition (91% and 87% respectively). More importantly, although the interaction between condition and prime type was not significant, an analysis of simple effects showed that in the long-SOA-strong-context condition, unrelated antonym primes produced interference as compared to neutral number-primes (84% and 90% correct responses respectively, F(3,138) = 4.27, p <.04), which was not the case in the short-SOA-weak-context condition (91% and 91% respectively). In addition, whereas number-primes had roughly the same effect on response accuracy in the two delay-context conditions (90% and 91%, F <1), unrelated antonym primes produced more interference in the long delay than in the short delay condition (84% and 91% respectively, F(3,138) = 6.04 p <.02).

Response Time

A 2 (prime type: related antonym or neutral number) by 2 (prime language) by 2 (target language) by 2 (preview type) by 2 (delay-context) by 2 (order of presentation) analysis of variance was performed on the response time data. There were significant main effects of prime type (F(1,46) = 3.99, p<.05), preview type (F(1,46) = 15.47, p<.001) and target language (F(1,46) = 102.03, p<.001). Test words were identified faster (1) when preceded by related than by neutral primes (609 and 636 msec respectively), (2) when the preview was identical to the test word than when it was a string of Xs (598 and 674 msec respectively), and (3) when the language of presentatation of test words was English as compared to French (554 and 691 msec respectively). The main effect of delay-context condition was not significant (F<1), however several interactions revealed that in fact the different factors had quite different effects in the two conditions. To facilitate the understanding of these effects, we shall present the two conditions separately.

Prime-Target	Eng-Eng			Fre-Eng			Eng-Fre			Fre-Fre		
Prime Type	Rel	Neu	Unr	Rel	Neu	Unr	Rel	Neu	Unr	Rel	Neu	Unr
Short SOA												
Id. Preview	493	585	500	547	570	557	631	733	684	605	643	752
% correct	100	96	100	98	92	90	83	92	81	88	85	83
Xs Preview	523	554	580	624	589	565	832	711	753	644	684	661
% correct	98	94	98	96	98	94	85	83	92	94	92	90
Long SOA												
Id. Preview	451	543	549	550	522	589	658	691	661	639	701	698
% correct	96	100	83	92	98	94	83	79	77	85	79	77
Xs Preview	550	576	584	583	600	635	711	705	788	701	765	709
% correct	94	96	90	98	100	94	90	81	81	85	85	79

Table 1. Mean response time (in msec) and percent correct in the short SOA and long SOA condition as a function of prime and target language (Eng = English, Fre = French), prime type (Rel = related, Neu = neutral, Unr = unrelated) and preview type (Id. = identical, Xs = XXXXX).

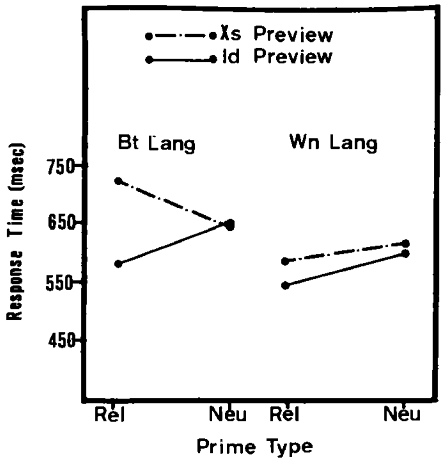

Figure 1. Mean response times in the short SOA condition for between- and within-language conditions as a function of prime type and preview type.

Short-SOA-weak-context condition

There was a main effect of target language ($F(1,46) = 58.57$, $p<.001$), with test words being identified faster when presented in English as compared to French. There was also a significant interaction between prime language and target language ($F(1,46) = 17.87$, $p<.001$) which revealed a strong effect of language compatibility. Response times to test words were considerably faster in within-language than in between-language conditions. In addition, there was a marginally significant two-way interaction between prime language, target language and preview type ($F(1,46) = 3.81$, $p<.06$, see Fig. 1). The facilitation produced by identical as compared to X previews was essentially found in the between-language conditions. Moreover, in the between-language conditions there was a significant interaction between prime type and preview type ($F(1,46) = 6.75$, $p<.01$). When the preview was identical to the test word, related as compared to neutral primes reduced response times, whereas when the preview was a string of Xs they increased response times. This interaction was not apparent in the within-language conditions ($F<1$), nor was there a significant main effect of preview type ($F(1,46) = 1.08$, ns); only the main effect of prime type was significant ($F(1,46) = 5.68$, $p<.02$).

The significance of these interactions can be explained by the following hypothesis. Let us suppose that the process by which a word is recognized involves two kinds of processes, the first being an automatic activation process, and the second a more central search process operating on the outcome of the first process. Upon the presentation of a word, two distinct levels of the lexicon are successively and automatically activated. The first, lower level is comprised of two independent perceptual systems corresponding to French and English, where orthographic information is stored. The second level is a common semantic system for the two languages, where meaning is represented and where semantic priming effects originate. The search process leading to lexical identification operates at both of these activation levels in such a way that the identification of a word consists in (1) finding the activated meaning of a word at the semantic level, and (2) finding the corresponding perceptual form activated at the lower, perceptual level of analysis. The correspondence between meaning and perceptual form is sought in only one perceptual system (language) at a time, the language "on-line" being normally that last searched by the central processor. If the corresponding perceptual form is not found in the language searched, languages (perceptual systems) are commuted, and the correspondence is sought in the other language.

We need here add the stipulation however that spelled-out numbers are accessed via numeration systems that are independent of the systems activated by meaningful words. Indeed, when the preview was a string of Xs (thus excluding the possibility of language induction by the preview), we observed a significant two-way interaction between prime language, target language and prime type ($F(1,46) = 6.02$, $p<.02$ see Figure 2). This interaction demonstrates that the effect of language compatibility was strong when the prime was a related antonym ($F(1,46) = 15.63$, $p<.001$) but near null when the prime was a number ($F(1,46) = 1.08$, n.s.). This indicates that our number-primes were neutral in concern to language information as well as semantically. Thus it can be assumed that following number-primes either language will randomly be put on-line for the next lexical research.

Given this stipulation, the process outlined above readily explains the interactions observed as well as the role played by the preview. When a related antonym prime is presented, its perceptual form, its meaning, and to a certain degree the meanings of several semantically related words are automatically activated. The activated perceptual form corresponding to the activated meaning will then be sought by the central processor in the perceptual system (language) currently on-line. If the perceptual unit (word) is not found therein, languages are commuted, the other language is put on-line, and the search continues. This explicits how the prime word (1) is identified, (2) activates related meanings, and (3) puts on-line the language in which perceptual forms will be sought.

Now consider what transpires in the between-language conditions, and the role of parafoveal

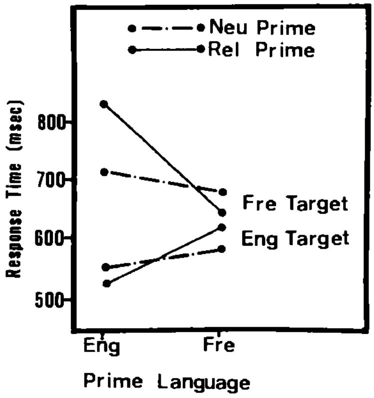

Figure 2. Mean response times in the short SOA condition for X previews, as a function of prime type, prime and target language.

information in these conditions. If a related prime word is followed by the presentation of an X preview, the location of the test word is indicated but no language information is provided and the perceptual system searched will be that put on-line by the prime. Hence, while the meaning activated by the prime corresponds to that of the test word, the incorrect perceptual system is on-line and is searched first, thus resulting in a loss of time. However, if the preview is identical to the test word, not only location but new language information is as well provided. The process of identification of the preview leads to language commutation and the putting on-line of the correct perceptual system. Thus both the meaning and the perceptual system activated correspond to the test word, and the effect of semantic priming is observed. Assuming that identical previews led to language commutation in a non-negligible number of instances, this would explain both the facilitation and interference produced by related prime words when followed by identical and X previews respectively. If the prime is a number-prime, either language may be randomly put on-line. Thus the fact that X previews do not provide language information is only hindering in a certain proportion of instances. Identical previews should however have led to language commutation in all instances that the incorrect language had been put on-line. The fact that identical previews did not significantly reduce response times in neutral prime conditions indicates however that they did not lead to language commutation when preceded by number-primes. This accounts for the structure of the observed interaction between prime type and preview type in the between-language conditions.

The effect of parafoveal information would be rather different in the within-language conditions. In these conditions, the language put on-line by the related prime word was always concordant with that of the test word. Thus, all information necessary (in terms of meaning and language) for the identification of a test word was provided by the related prime. Given this, the only useful role of previews was to indicate the location of target presentation, and in this sense identical previews were no more informative than X previews. This accounts for the fact that in the within-language conditions identical previews, as compared to X previews, did not noticeably facilitate word recognition. Number-primes provided neither semantic nor language information, whereas related primes provided both, thus accounting for the main effect of prime type.

In summary, in the short-SOA-weak-context condition, related foveal primes produced semantic facilitation in both within- and between-language conditions. The essential role of identical previews was to specify the language of the target word in the instance that this language differed from that of the prime. The effect of identical previews was apparent only when these previews were preceded by semantically related primes, and was reliable only when the languages of presentation of the prime word and the preview differed.

Long-SOA-strong-context condition

Quite a different picture arises in this condition. The interaction between prime language and target language was not significant ($F<1$). Response times to test words were not noticeably different in within- and between-language conditions. There were significant main effects of target language ($F(1,46) = 88.68$, $p<.001$) and of preview type ($F(1,46) = 9.63$, $p<.01$). Test words were identified faster when presented in English as compared to French, and when preceded by identical as compared to X previews. The main effect of prime type was marginally significant ($F(1,46) = 3.46$, $p<.07$) as was the two-way interaction between prime language, target language and prime type ($F(1,46) = 3.44$, $p<.07$). Separate analyses of within- and between-language conditions revealed that in the between-language conditions the effect of prime type was not significant ($F<1$) and that of preview type only marginally so ($F(1,46) = 2.83$, $p<.10$ see Fig. 3). In the within-language conditions, there were main effects of prime type and preview type ($F(1,46) = 6.57$, $p<.01$, and $F(1,46) = 7.42$, $p<.01$ respectively, see Fig. 3). Also, in the English within-language condition there was a significant interaction between prime type and preview type ($F(1,46) = 4.15$, $p<.05$).

The effects observed in this condition differ in two major aspects from those observed in the preceding condition. First, identical previews significantly reduced response times to test words in within-language conditions but only marginally so in between-language conditions, and the effect of previews was in most cases independent of prime type. The extended delay between prime offset and preview onset may very well have allowed subjects to complete foveal prime processing and to attend to parafoveal stimuli, thus enabling the processing of previews independently of primes, which was not the case in the short SOA condition. This is corroborated by the comparison of results obtained by McClelland and O'Regan (1981, experiment 1) showing that identical previews facilitated target processing when there was no central word to process, and the results of Paap and Newsome (1981, experiment 2) which showed that the simultaneous presentation of an unrelated word in central vision along with a parafoveal stimulus impeded the processing of parafoveal information.

Secondly, related antonym primes sped word recognition in within-language but not in between-language conditions. It would appear that in the present condition priming was due to strategic processing, as was indicated by the interference effects observed on response accuracy. The origin of the priming effect observed in this condition is thus quite different from that of the priming effect observed in the short SOA condition. Whereas in the latter condition priming was automatic, originated at the semantic level common to both languages and was thus independent of language, in the present condition it appears that priming resulted from the strategic predicting of a particular perceptual form (word) in a given language (that of the prime). By the term "predicting" is understood the finding of the meaning of the antonym at the semantic level, the searching for and the "marking" of the corresponding perceptual unit in a given language. When the actual test word is presented and activates the perceptual system, confirmation takes place, that is, it is confirmed whether or not the perceptual unit activated by the target is indeed the predicted, marked unit. This process would have the advantage of enabling confirmation without necessitating the semantic processing of the target word since such would have been done at the time of prediction. Predicting a target would moreover accelerate the identification process first, because the marked entry would be found faster in the lexicon, and secondly because the required level of activation would be lower for a predicted unit. The absence of priming effects in the between-language conditions indicates that predictions were successfully made only in the language put on-line by the related prime.

The effect of preview type can be explained by two hypotheses. It may be that identical previews facilitated in themselves the processing of test words. The fact that identical previews did not significantly facilitate the identification of test words in the within-language conditions in the short-SOA-weak-context condition, even when preceded by related primes, led us to another hypothesis similar to that proposed in the preceding condition.

Let us suppose the following process in the long SOA condition: (a) the subject identifies the meaning and the language of the related prime; (b) he then seeks and marks its antonym in the same language, while watching for the appearance of parafoveal information which is of greatest priority (localization of the target); (c) if he has time, he commutes languages in order to find the antonym in the other language, while still watching for a signal from the periphery; (d) again, if he has time, he searches the second language and marks the antonym in this language.

Assume that at a 740 msec delay, the peripheral information generally appears at the end of phase b or phase c, with a non-negligible probability in each case (p(b) and p(c) respectively), but almost never at the end of phase d (which explains the absence of priming effect in between-language conditions). Whichever be the language of the related prime, the identical preview, when identified or at least when searched for until the commutation of languages, usefully commutes language with a probability of p(c) in within- language and p(b) in between-language conditions. The same general schema applies for number-primes, however in this instance neither the semantic system nor the perceptual system of a meaningful word is activated. Rather, the subject will put on-line either language at random given that he knows target words can be presented in either language. Thus, following number primes, identical previews would usefully commute language in the instance that the language randomly put on-line was not that of the target.

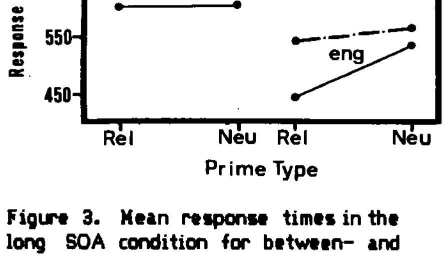

Figure 3. Mean response times in the long SOA condition for between- and within-language conditions as a function of prime type and preview type.

This process would in general account for the facilitation produced by identical previews, given that in this delay-context condition previews can be processed independently of prime type.

The interaction between prime type and preview type observed specifically in the English within-language condition can be explained assuming that, in phase b, the antonym of the prime word is found quicker and with a greater probability when searched in the English perceptual system (recall that the first language of our subjects was English). In this case, there is a greater probability that phase c was completed, and consequently that the language had been commuted to French. The result is that, if the preview is uninformative with respect to language, when the target appears the incorrect perceptual system is on-line and the benefit of prediction may be lost. Conversely, if an identical preview is presented, the processing of the preview puts on-line the correct language and benefits accrued from accurate predictions are obtained. This thus explains the structure of the interaction between prime type and preview type in the English within-language condition.

GENERAL DISCUSSION

The results observed in the short-SOA-weak-context condition revealed that the identification of foveal target words was facilitated by the prior parafoveal presentation of these words only when the parafoveal preview was preceded by a semantically related prime word. At first sight, this finding seems to corroborate the idea that parafoveal word processing is not only facilitated by preceding context but indeed contingent upon such. However, our findings in the long-SOA-strong-context condition (where previews were presented 600 msec after prime offset) showed that, when given enough time to complete the processing of foveal words, subjects were able to process parafoveal words independently of foveal prime words. This result is compatible with those observed in experiments where no central word was presented (Rayner, 1978; Rayner et.al., 1978; Rayner et.al., 1980; McClelland and O'Regan, 1981, experiment 1) or where subjects were given sufficient time to complete the processing of foveal contexts (McClelland and O'Regan, 1981, experiment 2). Given this, it cannot firmly be concluded that the processing of parafoveal information was dependent upon a related foveal context. What can be said from our data is that, at relatively short delays between foveal context offset and parafoveal stimulus onset, the foveal context must bear a relationship to the parafoveal word for facilitation to be produced by the latter; if the two words are not related it appears that the processing of the foveal context impedes the processing of the parafoveal word. We should like to further add however that in the short SOA condition, given the delay between the onset of the prime word and the preview word, the low proportion of trials in which prime words were followed by related words, and the absence of interference effects in this condition, it cannot be claimed that our subjects were actively predicting target words. Rather, the facilitating effect of prime words on preview processing that we observed appears to be the result of automatic semantic activation processes.

Whereas it may come to mind that subjects may have been looking to the right of fixation prior to the onset of previews, and thus actually viewing these stimuli foveally, the results obtained in the analysis of response times to nonword targets provides evidence contrary to this idea. If such were true, identical as compared to X previews should have produced facilitation for nonwords. This however was not verified by the results, the non-significant difference in response times between the two preview conditions being only 5 msec.

A word should be said about how a parafoveal preview of a target word facilitated the identification of this word when presented in foveal vision. First, it is important to keep in mind that our experiment was conducted with bilingual subjects and that previews were presented both in the first (English) and second weaker language (French) of these subjects. In the present experiment, despite our subjects' poorer performance (in terms of speed and accuracy) in identifying foveally presented target words in their second language as compared to first, there was no evidence that parafoveal words were processed differently or to a lesser extent when presented in French as compared to English. Thus the language of the preview in itself did not appear to differentially affect performance. In fact however, this does not necessarily imply that French previews were identified as well as English ones, which indeed would be surprising given the results observed for target words. It must be recalled that the essential role of the preview in the present experiment seems to have been to commute languages, from the language of the prime word to that of the target word in the instance that these two languages differed. In accordance with the process described in the results section however, it is not necessary that the preview be completely identified in order for languages to have been commuted. In fact, it suffices that the process of identification of a preview be undergone and that lexical search be carried out without success in the language on-line for languages to have been automatically commuted. This does nonetheless imply that the process of identification of the preview was at least engaged upon, which appeared to be the case in the short-SOA-weak-context condition only when previews were preceded by semantically related prime words. It can thus be deduced that the process of automatic activation, prior to identification itself, depends on the semantic interactions between the prime and the parafoveal preview. Our hypothesis is that the parafoveal preview provides degraded perceptual information which only weakly activates the perceptual entry corresponding to this word in the lexicon. This entry would therefore furnish a rather weak signal which would only moderately activate the corresponding semantic entry. If however this entry is already pre-activated by the prime, the combination of the two activations would give rise to a signal detectable by the central identification processor, thus leading to the active search for the perceptual unit. On the other hand, if the semantic entry is not pre-activated by the prime, the perceptual signal triggered by the preview would not in itself be strong enough to lead to a signal detectable by the corresponding semantic unit, and the identification process would thus not be undergone.

It should be noted that similar effects could be obtained, in the short delay condition, by supposing that semantic pre-activation is directly provided by the perceptual entries themselves, which corresponds to two different types of models. The effects could be obtained with a model supposing that there exists between lexical entries a network of activating relationships which themselves depend on the proximity of meaning. If such be the case, it must be supposed that these relationships exist as well between different languages as we would otherwise not have observed priming effects in the between-language conditions in the short delay condition. Between-language priming effects could as well have been obtained by supposing that there exists a level of semantic processing that sends activating feedback to the lexical entries corresponding to these meanings, which thereby constitutes an interactive system (Morton, 1969; Becker, 1980).

Nevertheless, according to both of the models described above we should have observed an effect of semantic priming between languages in the long delay as well as in the short delay condition since these models generally account for priming effects observed at as long if not longer delays than the one we used. Our results showed however that in the long delay condition there was an effect of semantic priming only in the within-language conditions. We might thus suppose that the strategic process of predicting words engaged upon at this delay (as a result of the strong context and instructions given to subjects) led to the inhibition of entries corresponding to non-predicted words, with predictions being made only in the language corresponding to the prime word. If this were the case however, related primes should have induced an effect of inhibition in the between-language conditions in the long delay condition, which was not apparent in the data.

It ensues that the interpretation we proposed above appears to be the only one, to our knowledge, that can account for the entirety of the results observed in the present experiment. Nevertheless, this does not prove that another type of model unknown to us could not fit our results equally well, and it should be noted that our motive for rejecting the above mentioned alternatives is based on the absence of an effect of the prime in the between-language conditions at the long delay, in other words upon the hypothesis of a null effect which indeed should be taken with caution.

The same remark partially applies to our interpretation of the effect of the preview. Indeed, while it is clear that the preview did in fact serve to commute languages, nothing allows us to conclude that the preview did not in itself have a facilitating effect when it was processed. It would indeed be surprising that the preview did not have some effect of its own, given the results obtained by other authors in monolingual situations (Rayner, 1978; Rayner et.al., 1978; Rayner et.al., 1980; McClelland and O'Regan, 1981) indicating that the identical parafoveal presentation of later presented foveal target words can facilitate the processing of these words. In fact, certain data in our experiment revealed tendencies which, although non-significant, were in the direction corresponding to a proper effect of previews even when the problem of language commutation was not logically posed. This was for example the case in the within-language conditions at the short delay, where the simple effect of identical as compared to X previews, when preceded by semantically related primes, was not significant but in the right direction (549 and 583 msec for identical and X previews respectively, ($F(1,46) = 2.18$, $p<.15$).

In conclusion, if we consider that the short SOA condition with semantic priming is most likely similar to the situation of normal reading, it appears that parafoveal words are processed not only at a purely perceptual level, but, to a certain extent, at a semantic level as well. Due to the relatively weak signal provided by parafoveal words however, it does seem as though the semantic processing of these words is completed only when their meaning is pre-activated by sufficiently strong contexts.

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PERCEPTUAL ANALYSIS OF WORDS IN ARABIC

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We showed, using a lexical decision task in Arabic, that when words differing by only one letter are presented in the experiment, there is perceptual competition between these words. The effect of this competition on lexical decision time increases with the rank of the differentiating letter, with ranks being counted from right to left in Arabic. This generalizes results previously obtained in French, where the ranks of letters are counted from left to right.

INTRODUCTION

Experimental research conducted in the last decade on word perception during reading has led many authors to abandon the idea that words are perceived and integrated as global units. McClelland (1976) demonstrated, for example, that the "Word Superiority Effect", a strong argument for the globalist view, is unaffected by aLtErNaTiNg case, which destroys the visual shape of words. This would imply that word recognition results from the analysis of the letters of a stimulus, being as letters are the only perceptual units that preserve their shape when case is alternated. Various other studies have since confirmed this hypothesis (see for example Johnston and McClelland, 1980; McClelland and Rumelhart, 1981; Rumelhart and McClelland, 1982; Paap, Newsome, McDonald and Schvaneveldt, 1982), and it now appears clear that the overall shape of a word does not play an appreciable role in the process of word recognition (Paap, Newsome and Noel, 1984). Letters would thus be the basic orthographic units, even though certain larger units such as "Functional Spelling Units" (e.g. CH, OU, TH) seem to be implicated in the formation of a phonetic representation of a stimulus (Pring, 1981).

It appears that letters are units composed of two levels corresponding to one or more visual definitions, and to a conceptual (alphabetical) definition, with the two levels being distinct and equally active in perceptual processing (Egeth and Santee, 1981). For example, "a" and "A" do not have the same visual definition but would share a common conceptual definition. Evett and Humphreys (1981) found that the codes used in lexical access are abstract graphemic codes, which are distinct from visual representations. We ourselves (Courrieu, 1985) found that the mental alphabet can be abstract to such an extent that the spatial and/or serial positions of letters comprised in a word would not be taken into account in the definition of alphabetical units, which would thus imply that at this level of coding two anagrams such as ARC and CAR have the exact same representation. If positional information is not associated with alphabetical codes, it must be assumed that a reader employs some other means for representing the order of letters in a word, without which anagrams would be indiscernable. It seems in fact that partial integration of letters in the form of digrams is carried out in perceptual analysis. These digrams themselves would however most likely be calculated from non-positional alphabetic codes, since it has been shown that inverse digrams (for example AM and MA) are not perceptually independent (Courrieu, 1985). This thus leaves unsolved the question of how ordinal information is initially encoded. A possible solution consists in supposing that letter order is transitorily represented in a dynamic fashion, that is to say upon a time axis. This would be possible provided that the different letters in a word are not simultaneously but rather serially encoded by means of a scanning process operating in the same direction as the writing system of the language. It is generally believed that non-meaningful letter strings are analyzed serially, however the great majority of authors reject this hypothesis in so far as words are concerned (see for example Henderson and Henderson, 1985). We ourselves have conducted various studies, given the theoretical necessities outlined above, examining the hypothesis that words as well are analyzed serially. For example, we (Courrieu, in press A) found that when a rapidly presented four letter word is preceded by a pre-mask containing one letter, which is not a letter of the word, and three non-alphabetic characters, the time of exposition being such that the temporal succession of stimuli is not always perceptible, the probability of identifying a word increases linearly as a function of the rank of the letter of the word where the alphabetic mask was placed. It appears as though the ambiguity concerning the identity of the alphabetically masked letter is lifted in accordance with lexical necessities with a greater and greater probability as this letter is positioned to the right (for words in French). The French lexicon is such that the a priori predictibility of a letter is not a monotonic function of the position of this letter in itself (Courrieu, 1983). We moreover verified in our experimental material that the predictiblity of a masked letter in context, this context being the set of non-masked letters of a word, is not a monotonic function of the rank of the masked letter. The critical factor appears to be the length of the context presented to the left of the masked letter, which suggests that the observed effect is linked to some type of sequential constraint that indeed increases as a function of the rank of the letter. We concluded that, in French, a word is analyzed serially from left to right by a process that continuously interacts with lexical access.

A posterior result led us to similar conclusions (Courrieu, in press A and B). This result is of particular importance to the present research, conducted in Arabic and which will be outlined below, since indeed it constitutes the point of departure of this experiment. In an experiment conducted in French, we presented words and nonwords of five letters in a lexical decision task. The sucession of trials was such that certain stimuli were presented several times in the experiment. However, at certain points we introduced distracting stimuli that differed from the preceding stimuli by only one letter (paragrams), with the serial position of this letter being experimentally varied. For example, we disrupted COEUR with SOEUR for rank 1, FORME with FERME for rank 2, TITRE with TIGRE for rank 3, BAGUE with BAGNE for rank 4, and lastly TEMPS with TEMPE for rank 5. The repetition of a target stimulus in the experiment accelerated response times in general. However, the introduction of a distracting paragram induced a relative delay in response time to a target stimulus when this stimulus was presented again. The size of this delay depended on the rank of the differentiating letter in the distracting stimulus (see Table 1). When the stimuli were French words, the induced response lag increased linearly as a function of the rank of the differentiating letter in the distracting paragram stimulus, whereas nonwords showed a non-monotonic function. We thus hypothesized that the introduction of paragrams in the experiment gave rise to perceptual competition between the different lexical possibilities presented, and that the observed response lag was none other than the delay required to find the letter which differentiated targets from their paragrams. This delay increased by approximately ten milliseconds per rank of the discriminating letter, which therefore led us to the concluson that in Frecnh a word is serially explored from left to right at a rate of ten milliseconds per letter. It is evident that such a rapid rate cannot be obtained other than by means of a relatively internal analysis process that probably operates on an elaborated representation of the stimulus. This corresponds most likely to an intra-fixation scanning process, however it should be noted that this scanning proceeds in the same direction as that of normal ocular scanning which itself corresponds to the direction of writing in the language.

	RANK OF THE DISCRIMINATING LETTER				
	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5
Words	-16.6	- 8.9	- 4.5	15.8	13.7
Nonwords	- 4.3	18.7	- 6.0	-21.5	- 2.3

Table 1 . Mean response lag (in msec) for French words and nonwords as a function of the rank of the letter which differentiates the stimulus from its paragram introduced in the experiment (after Courrieu, in press A and B).

Given these results, it seemed interesting to study this process in languages written in a different direction than French, as is the case of Arabic which is also an alphabetical language but which is written from right to left. Written Arabic has a number of other particularities that merit study. For example, in Arabic the inclusion of certain characters, in particular short vowels, is facultatory (and they are normally omitted). Graphically, these characters are employed somewhat like diacritics which are added to a word, above or below consonants, and which are often considered as modifications (the vocalization) of these consonants. Short vowels in Arabic are thus written out of the "ductus", the ductus being, according to the definition given by Blachere and Gaudefroy-Demombynes (1975), the sequence of letters which must be written (consonants and long vowels), in other words the "framework" of a word. Since short vowels are rarely written, readers of Arabic are accustomed to infering them rather than actually reading them. G. Roman (1982), in collaboration with B. Pavard, demonstrated that the addition of short vowels actually slowed down the reading process, and that readers of Arabic normally infer these vowels in accordance with certain vocalic schemas which depend on the grammatical category of the word (thus likely on the contextual constraints present in normal reading).

The present experiment is a quasi replication in Arabic of that conducted in French described above. The Arabic paragrams were chosen so as to enable the distinguishing of analytic processes which take place inside and outside of the ductus, thus enabling us to determine the chronology of events.

METHOD

Subjects. Twenty volunteers who spoke fluent Arabic and were currently living in France participated in the experiment. These Arabic-French bilinguals came from one of four different Arabic speaking countries (Algeria, Iraq, Morocco, Tunisia).

Apparatus. The experiment was controlled by a micro-computer, with stimuli being presented on the video screen. The stimuli were presented in luminuous characters against a dark background and subtended a varying horizontal visual angle (since Arabic is written cursively and the different letters differ in width), but this angle was always less than 2 degrees. No fixation point was used. Subjects responded by pressing one of two keys on the keyboard (corresponding to word and nonword responses respectively). The experimental program delivered the stimuli and recorded responses and response times (in milliseconds).

Material. The experimental material was made up of 30 pairs of word paragrams and 30 pairs of nonword paragrams (the latter being orthographically regular and pronounceable). 10 words and 10 nonwords were used for practice. No mixed pairs of word and nonword stimuli were presented. The stimuli were all composed of 5 letters, 4 of these being in the ductus and the fifth being a short vowel. Word stimuli were taken from the nominative category (nouns and adjectives) and had a relatively high familiarity in standard Arabic. Two examples of stimuli as they were displayed on the video screen can be seen in Figure 1. As can be noted, the calligraphy of the stimuli is of good quality. In as much as possible, we avoided resemblances between non-paragram stimuli, particularly for those stimuli which were presented in the same experimental phase.

The following conventions will be used to describe the structure of stimuli. Consonants are designated by the letter C, long vowels by the letter V and short vowels by the letter v. The letter which discriminated two paragrams is underlined. For each type of structure, two symbolic representations are given, the one corresponding to the orthographic form and the other to the phonemic form of stimuli. The phonemic form is written in parentheses and should be read from left to right. The orthographic form, written outside of parentheses, should be read from right to left. In this form, the symbol v is written above its corresponding consonant, even though in reality the short vowel would be written below the consonant. There were six types of paragram pairs, with the structure of these pairs being the same for word and nonword stimuli. The six types of paragram pairs are presented with examples in Figure 2. From a phonetic standpoint, short vowels always correspond to a phoneme pronounced immediately after the consonant it bears upon. The structure of stimuli was thus such that the first two consonants were always vowelised either by a short or by a long vowel, and the last consonant (the leftmost represented by the orthographic form) was never vowelised.

Procedure. An experimental trial began with a warning tone, followed after 500 msec by the presentation of the stimulus. Subjects were to respond manually as rapidly and as accurately as possible by pressing the "word" or the "nonword" key in accordance with the lexical status of the stimulus. The stimulus was erased from the screen immediately following the subject's response, and the next trial began after a 10 second interval. This task, known as the "lexical decision task" presents the double advantage of being quite simple and logically dependent on the process of lexical access (see Coltheart, 1978).

The experiment was divided into 5 blocks of trials, each block being separated by a short interval and beginning with a series of 4 practice trials. The succession of experimental trials in each block was such that there were 12 sequences, the ones being quasi-randomly interspersed among the others, each sequence comprising 5 trials and being constructed with 2 paragrams. One of the two paragrams was presented during the first three and the fifth trials of the sequence, with the other paragram being presented on the fourth trial and serving as a distracting stimulus. The respective roles of two paragrams of a pair were inverted for half of the subjects. The insertion of stimuli was such that between two trials of an experimental sequence there was always at least one trial and at most three originating from other sequences (this latter constraint was not present in the experiment conducted in French). In each block there were 6 sequences of words and 6 sequences of nonwords. Among the 6 sequences of each stimulus category there was one of each of the 6 types of pairs of paragrams described above.

Dependent Variable. The principal dependent variable was the response lag in the fifth as compared to the third trial in an experimental sequence (dt = TR5 - TR3), this lag being expressed in positive or negative msec (a negative lag corresponding to an accelerated response). This variable can, in principle, be analyzed as an acceleration constant due to the repetition of the principal stimulus, plus a lag value that depends on the distracting paragram introduced in the fourth trial of a sequence. Additional analyses were performed directly on response times.

Statistical Analyses. Analyses of variance were performed with a program (VARIANA) adapted to micro-computers. Two random factors were included in the analyses: the Item factor (designating the pairs of paragrams) and the Subject factor. Three different F ratios were used: Fi as a test relative to the item population, Fs as a test relative to the subject population, and a Quasi-F (F") as an exact test that takes into account the different sources of variance (c.f. Winer, 1971, Wickens and Kepple, 1983). Our decisions were founded on the Quasi-F which is at the same time the most rigorous and the most appropriate given the design of the experiment. Both Fi and Fs are also provided so that the reader can verify the coherence of our conclusions according to the habitually employed criteria.

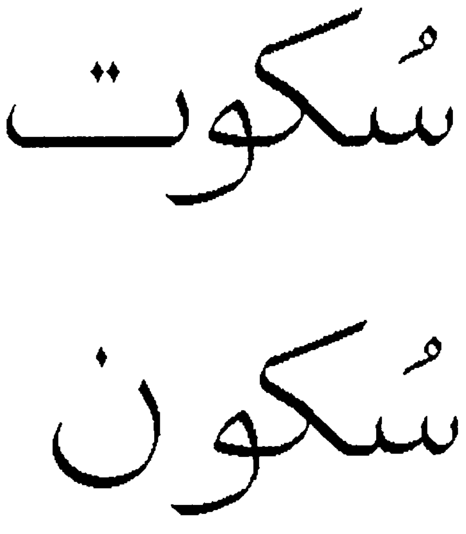

Figure 1 . Two examples (type 6 paragrams) of the calligraphy used in the experiment (screen copy).

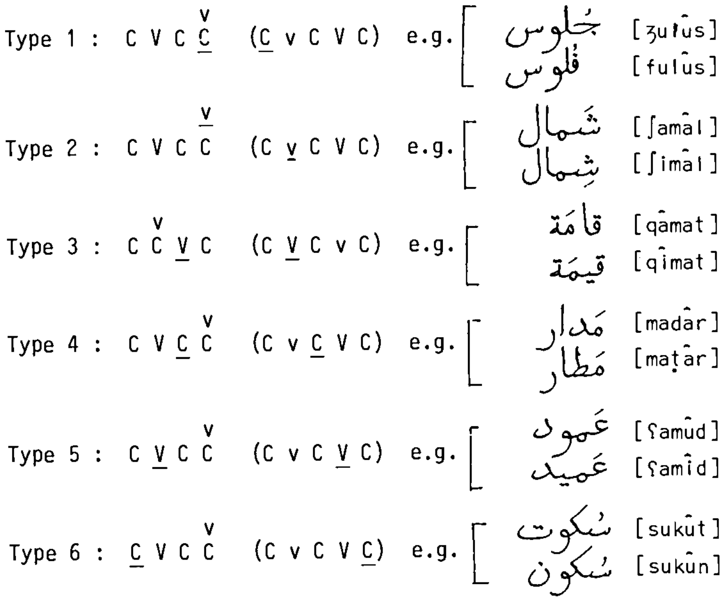

Figure 2. The six types of paragram pairs used in the experiment.

Hypotheses. Given the results of the preceding experiment conducted in French, we expected that the response lag observed in the fifth trial of a sequence would increase as a function of the rank of the letter differentiating the stimulus from its paragram introduced in the fourth trial, with the difference that in Arabic the ranks should be counted from right to left instead of from left to right. This result would thereby generalize the results we obtained in French (Courrieu, in press A and B) showing that a word is analyzed serially in accordance with the direction of writing in the language.

Nevertheless, the problem posed is somewhat more complex in Arabic as a result of the fact that short vowels are written outside of the ductus. Three possible consequences of this are outlined below:

A. If the short vowel is treated in the same manner as a diacritic that modifies the consonant it bears upon, then type 1 and type 2 paragrams should give rise to roughly equivalent response lags since in both instances the discriminating element is the first letter, i.e. the initial consonant. In addition, type 3 and type 4 paragrams should provoke equivalent response lags since in both cases the discriminating element is the second letter.

B. If the short vowel is treated in the same manner as a letter in accordance with its ordinary rank (as it appears in the phonetic form of a word) then type 2 and type 3 paragrams should result in equivalent response lags since in both cases the discriminating element is the second letter, i.e. the first vowel.

C. If the ductus is the main element examined and the short vowel ignored in the first analysis, then type 3 and type 4 paragrams should give rise to equivalent response lags since in both cases the distinctive element is the second element taken into account. Type 2 paragrams should lead to maximum lags since in these cases the discriminating element is the last examined one, i.e. the short vowel.

RESULTS

As far as word sequences are concerned, there was a significant effect of repetition, with mean response times decreasing from 1264 msec for the first trial to 767 msec for the third trial (Fi (1,96) = 299.42, p<.001, Fs (1,64) = 118.28, p<.001, F"(1,113) = 84.94, p<.001). The introduction of a distracting paragram in the fourth trial led to an increase in response time, which increased from 767 msec for the third trial to 839 msec for the fifth trial (Fi (1,24) = 46.12, p<.001, Fs (1,16) = 20.16, p<.001, F"(1,30) = 14.73, p<.001).

The nonword sequences gave rise to a rather similar evolution of response times, which went from 1556 msec for the first trial to 906 msec for the third trial (Fi (1,96) = 522.61, p<.001, Fs (1,64) = 130.79, p<.001, F"(1,96) = 104.75, p<.001), and which increased from 906 msec for the third trial to 1014 msec for the fifth trial (Fi (1,24) = 31.00, p<.001, Fs (1,16) = 8.98, p<.01, F"(1,25) = 7.17, p<.02).

The response lags in the fifth trial as a function of the type of paragram and in accordance with the lexical status of stimuli are shown in Table 2.

	TYPE OF PARAGRAM					
	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6
Words	10	111	36	83	100	93
Nonwords	151	192	63	25	137	80

Table 2 . Mean response lag (in msec) in the fifth trial of the sequence, relatively to the third, for Arabic words and nonwords, as a function of the type of paragram introduced in the fourth trial.

When word stimuli are considered, it can be seen that type 2 paragrams led to maximum response lags. This lag was significantly greater than those obtained with type 1 and type 3 paragrams (Fi (1,24) = 7.52, p<.02, Fs (1,80) = 5.97, p<.02, F"(1,83) = 4.03, p<.05). Hypotheses A and B can thus be rejected, since it appears that the short vowel is taken into account late in analysis. If type 2 paragrams are excluded from the analysis of response lags, thus retaining only those cases where the distinctive element is contained in the ductus, it can be seen that the response lag increases in a linear fashion with the rank of the distinctive element, as this rank appears in the phonemic form of stimuli. A significant linear componant was extracted (dt' = 23 X - 4.6, Fi (1,20) = 7.95, p<.01, Fs (1,64) = 5.95, p<.02, F"(1,70) = 4.07, p<.05), with no significant residual variance (Fi <1, Fs <1, F"<1). It should in particular be noted that the difference in response lags for type 3 and type 4 paragrams was far from being negligible, since the observed progression in response lags was 47 msec, which is greater than the mean progression of 23 msec estimated by the linear regression. Hypothesis C cannot thus be accepted without modification.

For nonwords, the profile of response lags differed from that observed for word stimuli. There was no significant main effect of paragram type, however the following tendancies were observed: the response lag for type 2 paragrams was greater than that observed with all other types of paragrams (Fi (1,24) = 3.73, p<.07, Fs (1,80) = 7.18, p<.01, F"(2,51) = 3.07, p<.06), and when type 2 paragrams are excluded from analysis the profile of response lags is best fit with a cubic function (Fi (1,20) = 2.42, p<.14, Fs (1,64) = 4.09, p<.05, F"(2,46) = 2.19, p<.13).

DISCUSSION

It seems safe to conclude that words are analyzed serially in Arabic, given the fact that the response lag observed for the fifth trial increased by approximately 20 msec per rank of the discriminating letter. This rate is close to twice that observed in French. The exact reason for this difference is not known to us, however various explanations are possible. It may be that the relative slowness of progression in Arabic is linked to certain characteristics of the language itself, since it has been shown that the mean time of gaze per word is longer in Arabic than in French (345 and 214 msec respectively, according to Roman, 1982). It may as well be that our Arabic subjects were slower as a result of their being bilingual, along with the fact that the large majority had read more frequently in French than in Arabic for a number of years. Lastly, it may be that our estimation of the rate of progression was biased. Suppose for example that the probability that the paragram, introduced in the fourth trial, interfered with the processing of the principal stimulus, presented in the fifth trial, was dependent on the number of stimuli interposed between trials. In the present experiment we had the added constraint that no more than three stimuli could be interposed between two stimuli of the same sequence. This constraint was not imposed in the experiment conducted in French, and in this experiment the expected number of interposed stimuli was 9, whereas in the present experiment this number was 2. Let us thus suppose that the probability of interference is twice as great in the present experiment, conducted in Arabic, as in the experiment conducted in French. When interference is produced, the serial process of discrimination of paragrams provokes a response lag $T(X) = KX$, where X is the rank of the distinctive element and K the time per letter, i.e. the true progression constant. When no interference is produced, there is no discrimination and as such $T(X) = 0$ whatever X is. Given the probability Pf that interference will be produced in the experiment conducted in French and the probability Pa that such will occur in the present experiment, conducted in Arabic, we have through hypothesis $Pa = 2\ Pf$, and thus the mean $Ta(X) = Pa\ KX = 2\ Pf\ KX = 2\ Tf(X)$, in other words a rate that is estimated two times slower in Arabic than in French ($2\ Pf\ K$ vs. $Pf\ K$) while in actuality the rate would be the same in both languages and would moreover be at least as slow as the estimated rate in Arabic. This latter possibilty is quite plausible, since in fact in Arabic we observed a significant increase in response times between the third and the fifth trial of a sequence, whereas the mean difference between these two trials in the experiment conducted in French was zero. This suggests that the interference effects were greater in the present experiment, and the repetition effect of the principal stimulus completely thwarted.

It may in fact be possible that several of the above mentioned explanations concurred to produce the difference in rate that we observed between the present experiment and that conducted in French, however the data do not allow any firm conclusions to be drawn.

We found in addition that the linear increase in response lags applied to the phonemic description of a word, that is to the form in which short vowels are integrated at their normal position. The paradox here is that when the short vowel was the discriminating character (type 2 paragrams), the results seemed to show that this vowel was not initially examined at its ordinary position but only afterwards, following the examination of the ductus. This can undoubtedly be explained by the normal reading habits of readers of Arabic. Indeed, it has been shown that readers of Arabic do not normally read short vowels but infer them (Roman, 1982). It is thus quite possible that the process by which paragrams are discriminated operates according to a representation of the stimulus where the short vowel is infered at its normal position but not read, and it is only in the particular instance that this vowel is in fact the discriminating element that the reader later truely reads this vowel, which would explain the structure of our results. This would further provide evidence that the forms upon which the discrimination process operates are in fact quite abstract, given that they integrate even inferred information.

When nonwords were considered, no monotonic serial effect was observed in Arabic, as was equally the case in French. This implies that, in this type of experiment, the serial analysis operating in the same direction as the writing system of the language specifically concerns the process of lexical discrimination and not the processing of nonwords, which thus inverts the conclusions arrived at in different experimental paradigms such as the comparison paradigms where two stimuli are simultaneously presented (Henderson and Henderson, 1975).

Lastly, our results show that a serial discrimination process intervenes when an ambiguity concerning the lexical identity of a stimulus is detected, this being true both in French and in Arabic. However, nothing can be said about how the initial phase of lexical access leads to the detection of ambiguities.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

DECOMPOSING FRENCH WORDS

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Subjects read words in such a way that their eye was positioned at either the beginning, the middle, or the end of the word. The middle of the word is usually the most convenient viewing position for the eye to commence scanning. It was expected that the convenient viewing position might shift towards the stem of a word containing either a prefix or a suffix. However, this was found to be the case only for extremely long words. Either French people do not usually decompose morphologically complex words during reading, or the eye's behaviour does not reflect this mental calculation.

Visual word recognition has tended in the past to be investigated by people from two different camps. On the one hand, there are researchers concerned with lexical access as a means of approaching the general problem of the structure of the mental lexicon. Although these researchers have for the most part concentrated on visual presentation of stimuli, this has often been merely a matter of convenience. On the other hand, there are researchers who investigate word recognition as an intrinsic part of the reading process as such. The measurement and manipulation of eye movements while a person is reading is one of the major experimental procedures used by the latter group. This technique yields a considerable amount of valuable information which cannot be obtained from global measures of word recognition time, such as lexical decision or pronunciation ("naming") latency. It thus seems appropriate to try to combine these two approaches, and the study we will report represents an attempt to show that such a liaison can be fruitful.

Using this eye-movement methodology, O'Regan, Lévy-Schoen, Pynte & Brugaillère (1984) have recently shown that there is an optimal position for the eye to start scanning a word. This optimal position is about the third or fourth letter of the word. If this is the region first fixated by the eye, fewer fixations are necessary to read the word, and the overall gaze duration on the word is lower, compared with if the eye commences at other regions, for example, right at the beginning or towards the end of the word. This finding makes sense, given that people process words basically left-to-right, and that this would allow the eye to have in central vision the first five or six letters.

O'Regan et al wondered whether this "convenient viewing position" remained constant for all words. They provided some evidence that if the "information-bearing" part of the word was at the end of the word rather than the beginning, the convenient viewing position shifted further into the word compared with words whose distinguishing information was at the beginning. Unfortunately, this evidence was not very strong, as only two positions of first fixation of the eye were tested (the first half vs. the second half of the word), and the effect was of marginal statistical significance. One aim of the present experiment was to try to show that this effect of information structure of words is a genuine effect.

The words O'Regan et al used were chosen in the following way. The first six letters of "beginning" words, such as "élucubration", "gymnastique", and "gladiateur" were not shared by any other words of about the same length; so their ends were predictable from their beginnings. The last six letters of "end" words, such as "hypernerveux", "contrepoids", and "superficie" were not shared by any other words of about the same length; and so their beginnings were predictable from their ends. However, it is clear that the words differed not only in their "predictability", but also in their morphological stucture. The "beginning" words contained derivational suffixes, while the "end" words contained prefixes.

Lexical access researchers have argued that morphological structure itself has a critical influence on word recognition. Taft & Forster (1975) and Taft (1979) have proposed that prefixed words are decomposed morphologically into their separate morphemes (prefix and stem) when they are recognised, and it is the stem that serves as the access code in the "peripheral visual access file" of the lexicon. If this prefix stripping takes place, does it mean that the convenient viewing position for prefixed words shifts towards the stem, the end of the word, compared with monomorphemic words? This was the next major question we asked in our experiment.

A similar proposal has been made for suffixed words. Taft (1979) found that, at least for inflected words (e.g., "likes", "liked", "liking"), lexical decision time was dependent on the frequency of the stem of the word when surface (whole-word) frequency was equated. This finding suggests that suffixes are also stripped off from the basic stem, which is the crucial portion for lexical access. Accordingly, would the convenient viewing position for suffixed words be shifted towards the beginning of the word compared with monomorphemic words? This was our final basic question.

Thus, we were hoping that the study of eye-movement behaviour might give us more precise information than whole-word tasks do about the influence of the internal structure of a word on its recognition.

The task that we used was designed to resemble so-called "normal" reading a little more than standard lexical access tasks often do. Subjects had to read a phrase of from two to five words and decide whether it was completely meaningful. Some examples of stimuli requiring a no answer are "aimable ou sablé" and "recopier la chaleur", and some examples of stimuli requiring a yes answer are "algèbre compliquée" and "réussir dans la vie". The target word is the first word, the rest of the phrase, the comparison word or words, is not of direct interest.

The subject sat before a VDU with her chin on a chin rest to minimise head movements, wearing spectacles that allowed eye movements to be monitored. On each trial a fixation point appeared, and when the subject fixated it, the target word appeared at one of five predetermined locations across the word. Thus, the eye commenced scanning at any one of these equally wide regions of the word. We used zones like this rather than specific letter locations because the words varied in the number of letters they contained. The comparison word or words appeared at the same time as the target word, but separated by three spaces and covered by a jumbled letter mask. As soon as the eye began to leave the target word, the mask lifted from the comparison word and descended on the target word, so that it was useless to look back at it.

The comparison word stayed on the screen until the subject made a decision, and then the subject was informed as to whether the response was correct or not.

Subjects were 50 Parisian university students whose native language was French.

We first of all wanted to determine whether we could produce a real shift in the convenient viewing position with the same words that O'Regan et al (1984) had used. That is, we had "beginning" words whose ends were predictable from their beginnings and "end" words whose beginnings were predictable from their ends.

Figure 1 shows the average gaze durations that we obtained for these words - that is, the sum of all the fixations on a word - plotted as a function of the zone the eye started in. It can be seen that the predicted U-shaped curve across the zone of first fixation was obtained for both conditions. However, the functions were by no means identical. The convenient viewing position for

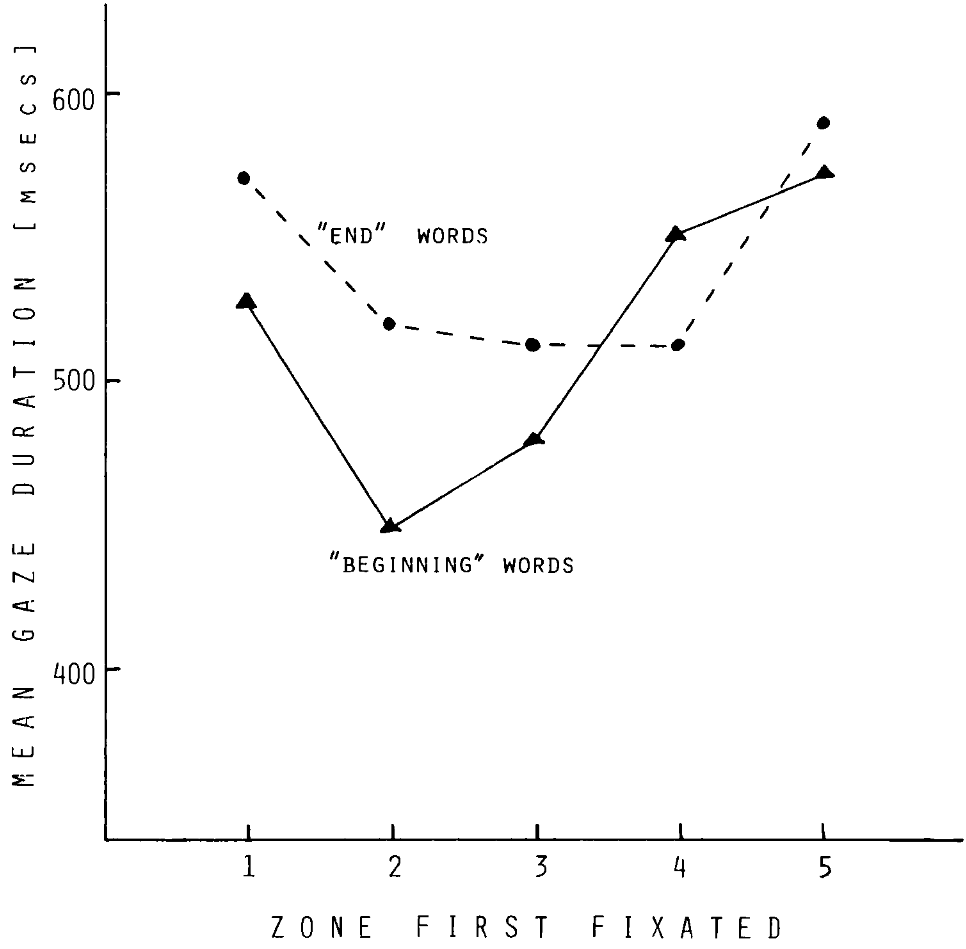

FIGURE 1: Mean gaze duration as a function of position of first fixation for words whose beginnings or whose ends were highly informative.

"beginning" words is the second zone, and these words have a processing advantage when the eye starts at the beginning or the middle. The convenient viewing position for "end" words is further along, at the third or even fourth zone. This interaction of zone of first fixation and word type was significant, with min F'(4,123) = 2.53. Thus, because we used five zones of first fixation rather than just two, we were able to show that the convenient viewing position does change depending on where the most "information" is.

We then wanted to compare affixed words with monomorphemic control words of the same length and frequency. The prefixed and suffixed words were treated separately, in two different designs.

We compared recognition of monomorphemic words like "pénétrer" and "terminer" with two kinds of prefixed words, those whose stems occurred freely as words themselves, like "contenir" and "prévenir", and those whose stems could not

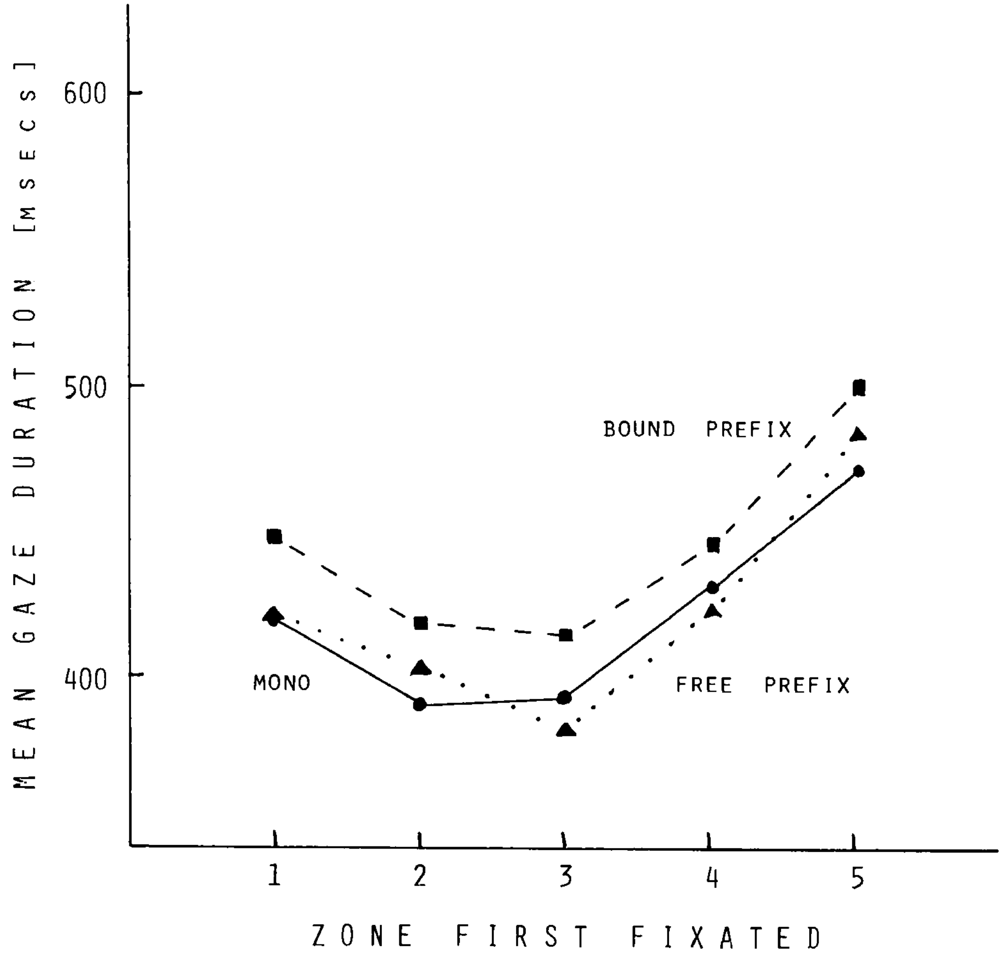

FIGURE 2: Mean gaze duration as a function of position of first fixation for high frequency prefixed words with free or bound stems and for monomorphemic controls.

occur independently as words, like "renoncer" and "préciser". According to Taft's theory, both types of stems should act in the same way: the word or non-word status of the stem is irrelevant. We also included a contrast between high frequency and low frequency triads of stimuli, as some recent work has suggested on other grounds that high frequency words may be accessed as wholes. If this is true, perhaps they may be less often decomposed morphologically than low frequency words. The above examples are high frequency items. Examples of low frequency items are - monomorphemic: "quereller" and "grimacer"; prefixed with free stem: "concourir" and "endurcir"; prefixed with bound stem: "conspirer" and "expulser".

The results for average gaze duration for the high frequency words can be seen in Figure 2. Again there is a convenient viewing position, but it is no further into the word for prefixed than for monomorphemic words. It remains at the second or third zone for all types. Interestingly enough, there appears to

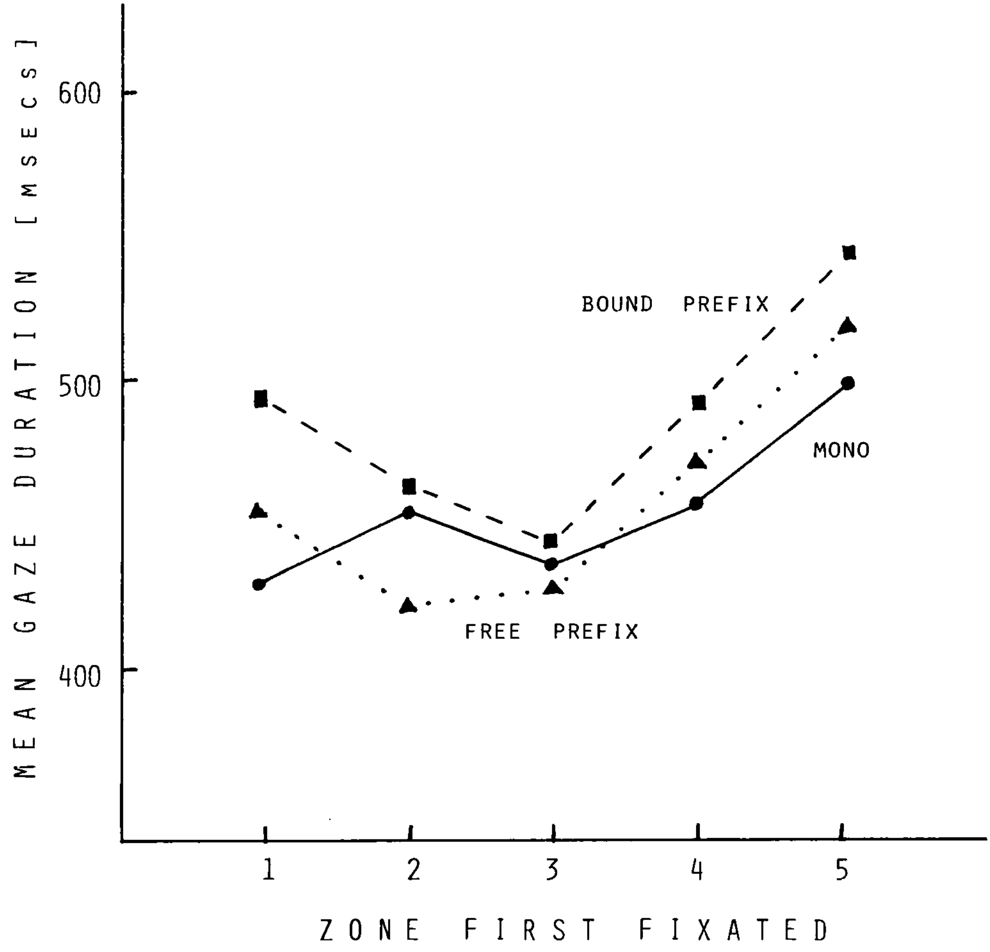

FIGURE 3: Mean gaze duration as a function of position of first fixation for low frequency prefixed words with free or bound stems and for monomorphemic controls.

be an overall effect of morphological structure - the prefixed words with bound stems took longer overall to read than the other two types.

The gaze duration data for the low frequency words are shown in Figure 3. These words required overall 36 msecs more processing time than the high frequency words, resulting in a significant main effect of frequency, with min F'(1,24) = 9.92. Again the convenient viewing position is at the second or third zone. The overall effect of zone of first fixation was significant, with min F'(4,162) = 24.06. But there was no change in the convenient viewing position for the different word types, even though the curve for the monomorphemic words is slightly irregular. There was no trace of an interaction between zone of first fixation and structure, with min F' < 1. Thus, there was no evidence that the convenient viewing position in prefixed words is further towards the end of the word than it is in monomorphemic words.

Despite this result, the prefixed words with bound stems again took longer to

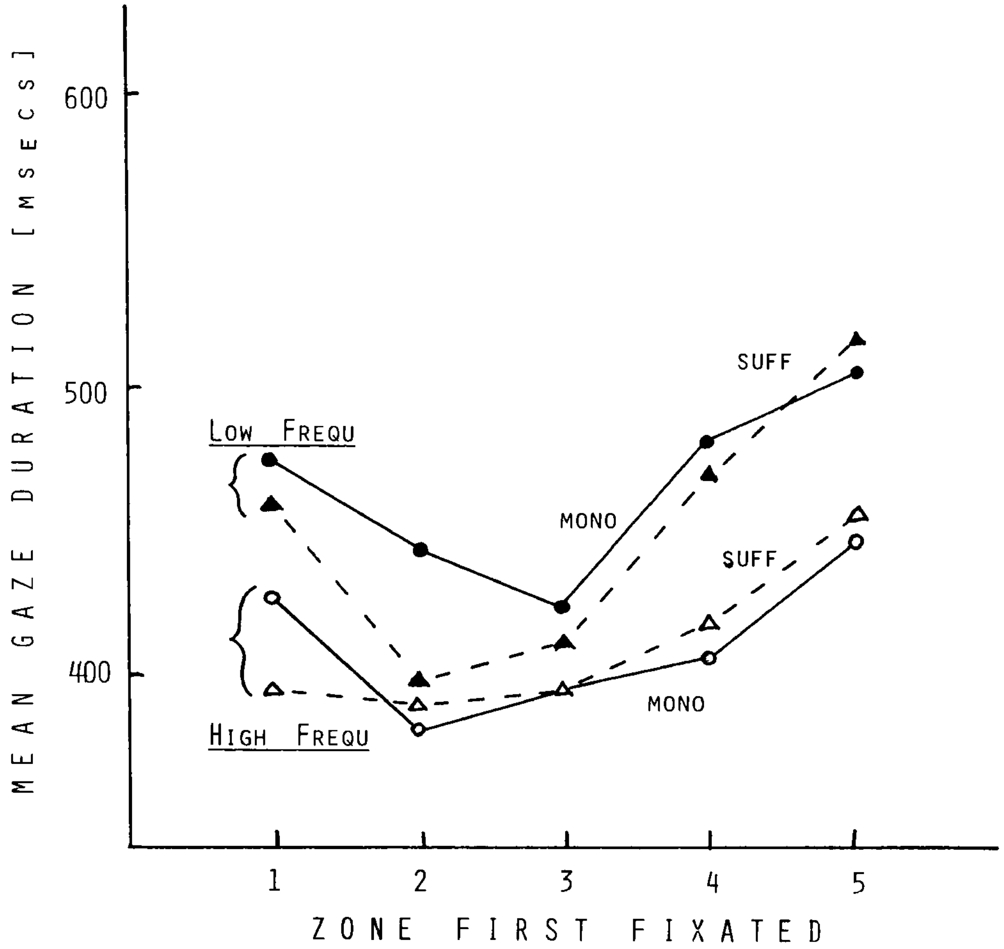

FIGURE 4: Mean gaze duration as a function of position of first fixation for suffixed words and for monomorphemic controls, both high and low frequency.

read than the prefixed words with free stems, which were not much different from the monomorphemic words. This 23 msec structural effect was significant, with min F'(2,55) = 4.42. We shall return to a possible explanation of this effect subsequently.

Considering now the suffixed words, we again had stimulus pairs of either high or low frequency. We examined derivational suffixes, rather than inflections, but we had just one type of affixed word. We compared monomorphemic words like "fatigue" and "mémoire" (high frequency) and "ballade" and "épargne" (low frequency) with suffixed words like "douceur" and "passage" (high frequency) and "lutteur" and "ombrage" (low frequency). Not all the stems were free words, but we tried to make them as close to free words as possible, often it was only a question of a missing "e".

Figure 4 shows the gaze duration results for suffixed words plotted across the zone of first fixation, this time for both low and high frequency words. The overall effect of frequency is quite apparent, and at 47 msecs, it was highly significant, with min F'(1,37) = 15.12. The convenient viewing position is again found at the second or third zone. Zone was significant, with min F'(4,39) = 28.94, but it did not interact with morphological structure, with min F' < 1. So our idea that the convenient viewing position might be earlier in suffixed than in monomorphemic words was not supported.

There was no overall effect of morphological structure, nor an interaction of frequency and structure, despite the apparent advantage of suffixed over monomorphemic words when they were low frequency. For both these effects, min F' < 1. The latter difference was caused almost entirely by the presence of one apparently unusual monomorphemic word.

In sum, we conclude that the convenient viewing position to commence scanning an isolated word generally remains at about the third or fourth letter in a word, regardless of its morphological structure. This is the position which allows the eye to look clearly at about five or six letters, which will usually encompass at least two syllables, and maybe one or two morphemes. Why, then, did we manage to change the convenient viewing position of O'Regan et al's words that had their primary information either at the beginning or at the end? For a start, these words were much longer than our other words, averaging 11 letters, compared with 7 letters for the suffixed words and 8 letters for the prefixed words.

For words 7 to 8 letters long, the probability of making only one fixation when the eye is at the convenient viewing position is more than 50%. In other words, the eye can quite often obtain enough information to identify the word in a single fixation. So, even if a portion of the word is more salient psychologically than the rest, this may not be reflected in longer inspection times of that region. Perhaps it is only when the word exceeds the visual span, and a second fixation (or more) is much more likely, that the eye inspection time reveals more "intense" cognitive processing.

Thus, for the long words, it is still basically an open question whether it is the "predictability" characteristics of the particular words we used, or their differential morphological structure, that caused the shift in the convenient viewing position. Although the convenient viewing position did not change as a function of morphological structure in our shorter words, there is one result from our experiment that does implicate subjects' sensitivity to morphological structure. For both high and low frequency words, prefixed words with bound (or non-word) stems took longer to identify than either monomorphemic words or prefixed words with free (or word) stems. This result seems difficult to explain without the postulation of some kind of pre-lexical stripping of prefixes, which has incurred a penalty in the case of non-word stems. That is, it implies that all prefixed words have their prefixes stripped off in search of the stem. If the stem is a word then successful lexical access can occur. If it is not a word, the prefix is attached back to the stem, and lexical access re-initiated on the basis of the whole word. It is the unsuccessful search and re-processing which may take the extra 23 msecs for the prefixed words with non-word stems.

If this argument is correct, then given that the stem of each of the prefixed words we used was more frequent than the entire word itself, it might be wondered why the prefixed words with free stems were not processed more quickly than the monomorphemic words with which they were matched in surface frequency. To account for this lack of difference, one would have to postulate a recomposition process which takes time. Access to the entry in the peripheral file may be quicker, but there would be an additional reconstitution process, presumably in the master file.

As far as suffixed words are concerned, while we have no evidence from our experiment that suffixes are stripped off during recognition, the same argument could perhaps be applied in their case. The stems of the suffixed words were more frequent than the whole word, and thus than the control monomorphemic words, so there would again have to be a costly recomposition process, cancelling out the time gained in accessing the lexical entry more quickly. Clearly, it would be desirable to have more direct evidence for these hypothetical decomposition and recomposition processes.

A final point concerns the fact that at first glance the results seem incompatible with Taft's hypothesis that word and non-word stems of prefixed words should act as access codes with equal efficiency. Could it be the case that only free morphemes function effectively as access codes? Perhaps such a modification to the theory may be necessary.

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EYE MOVEMENTS: From Physiology to Cognition
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SCANNING PATTERNS ON INDIVIDUAL WORDS DURING THE COMPREHENSION OF SENTENCES

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What determines the guidance of the eye during word recognition? The experiments reported here investigate the possibility that the informativeness of a specific region within a word can determine the duration of fixation and can also attract an eye fixation. In Experiment 1 words containing identifying information either towards the beginning or towards the end were displayed asymmetrically around the point of fixation, so that the reader was initially presented with either the informative or non-informative zone. Fixations upon the informative zones of words were longer only when those zones were at the beginnings of words; saccades away from the ends of words were longer than those away from the beginnings, and this trend was emphasised when the informative zone was at the beginning. In Experiment 2 the battery of words was presented in sentences which were to be comprehended, and fixation patterns around the informative regions were recorded. More attention was again given to the informative zones of words, and the locations of the fixations within words tended to be upon the informative zones. The results of these experiments lend good support to the hypothesis of immediate lexical control over fixation behaviour, and some support to the view that parafoveal information can be useful in guiding the reader's eyes to important parts of text.

INTRODUCTION

Is the eye fixation behaviour of readers under the moment-to-moment influence of ongoing processing, and if so, does this influence extend beyond the information currently being fixated? The two experiments described here investigate these questions by presenting subjects with words which are informative only at the beginning or at the end of the word. In the first experiment the words are presented in isolation, and in the second they were presented in sentences. In both cases readers were required to derive the meanings of these words. If fixation patterns are under the immediate influence of the informativeness of the parts of words being fixated, then a relationship should exist between information content and fixation duration, and possibly also between information content and fixation location. If readers tend to initially fixate the informative parts of words, with no prior knowledge of the location of this information other than that gained by non-fixated processing, then we would also have evidence that fixation patterns can be determined not only be what is being fixated but also by what is ahead of fixation.

O'Regan (1984) has reported a recent investigation of the relationship between the location of information within words and the pattern of eye movements around this information, and it is this series of experiments which provides the starting point for the present paper. In those experiments, and also those reported by O'Regan, Lévy-Schoen, Pynte, and Brugaillère (1984), readers were presented with long words asymmetrically about the point of fixation, with fixation coinciding with the third letter from the beginning or the third letter from the end. The information in each word was contained either within the first six letters or within the final six letters, with the remaining letters providing little or no information about the word's identity. The task was to name the word, or to perform an identity-matching task which required the comparison of the first (critical) word with a second word, or to judge whether two words were related in meaning. The experiments provided partial support for the idea that the eye is controlled according to the information content of the letters under fixation, but the results depended upon whether the initial fixation upon the word was towards the end or towards the beginning. An initial fixation upon an informative zone at the beginning of a word gained a long fixation, and an initial fixation upon a non-informative zone at the beginning gained a shorter fixation followed by a longer fixation upon the informative end of the word. So far so good: here we have evidence of the duration of fixation being influenced by the information being fixated. The lexical structure of the word was reflected in the fixation patterns, but the story is less clear for the case of an initial fixation towards the end of the word. If the first fixation was upon a non-informative zone then this was a very short fixation followed by a long fixation at the beginning, where the information was located. However, if the first fixation was upon an informative zone there was a short fixation here also. The first fixation was short regardless of whether or not it was upon the information in the word. So, initial fixations at the beginnings of words provide us with evidence in favour of the hypothesis of immediate processing, but fixations at the ends of words result in rapid movements to the left even when these take the information away from fixation. One explanation of O'Regan's "beginning-dominance" rests with the possibility that his naming and identity-matching tasks could be performed without lexical access. The naming task might have been performed by reference to non-lexical grapheme-to-phoneme correspondence rules (at least for some of the words used in the experiment), and the identity-matching task might have been performed with a visual matching strategy. Both of these non-lexical strategies could rely on an emphasis upon the beginnings of words. The semantic comparison task also found longer inspections upon the informative zones of words, and shorter inspections at the beginnings of words, and so the effects cannot be attributed to non-lexical, serial search strategies. The first of the experiments reported here further investigated the pattern of fixations within isolated words, in a task where the word must be processed for meaning, in an attempt to replicate Experiment 3 of O'Regan et al (1984), before using the sample of long words when inserted into sentences in a task which more nearly approximated to natural reading.

Evidence in favour of the stronger hypothesis of fixation control, which suggests that information ahead of fixation can attract future fixations, has come largely from tachistoscope studies of the information gained in a single fixation. These experiments have reported that words in the parafovea can influence responses to very briefly fixated words shown at the same time. The experiments are reviewed in Underwood (1985a, 1985b). The possibility raised by them is that if parafoveal words are recognised lexically in static presentations, they are also of importance during the reading of text. One possible way in which they can influence reading is by the provision of information about the meaning of the text, and another way is by providing markers about the location of words in the text which are of interest to the meaning of the text and which might gain future fixations (Underwood, 1981). Evidence in favour of the importance of parafoveal information was reported by Kennedy (1978) in an experiment in which associatively primed words were fixated sooner than when they were not primed. Only if they had been recognised in parafoveal vision could these words have influenced the latency of fixation. The experiment was simulated by Jennings and Underwood (1984) with a tachistoscope study using sequences of slides, and with a consistent result: the prior parafoveal exposure of a word influenced its subsequent processing when it was available to fixation. The reading experiment reported by Ehrlich and Rayner (1981) also provided evidence which can be interpreted in support of the view that fixation behaviour can be determined by the content of the text ahead of the current fixation. Specific words in predictable contexts were fixated less often than the same words in neutral contexts, and when they were fixated, they received shorter fixations. Further evidence in favour of the idea of semantic preprocessing acting to attract eye fixations was sought in Experiment 2, in which the words from Experiment 1 were presented in sentences. If the initial fixation upon a word tended to be within the informative zone of that word, then the question would be raised of how the eye knew of the location of the information if preprocessing had not occurred.

EXPERIMENT 1: READING ISOLATED WORDS

Subjects

Twelve Finnish-speaking adults (nine females) acted as subjects for the experiment. All had normal vision. A further 41 subjects from the same population aided in a study which was used to select the battery of words for Experiments 1 and 2.

Materials

Eighty Finnish words were selected for use in the experiment by a pilot study which had the intention of finding words which were identifiable by their end letters or by their beginning letters. Each word was between 10 and 13 characters in length, and 40 of them had identifying information at the end, and the other 40 had this identifying information at the beginning. Two word lists each had the 80 words appearing in them. If a word had only the first six letters visible in one list, then in the other list the same word had only the last six letters available for inspection. Both types of presentation appeared in each list equally often. Subjects were instructed that each word contained at least ten letters, but no indication was given of the exact length of any word. Twenty subjects performed the completion task with one list, and another 21 subjects were given the other list. The final battery consisted of 20 words with crucial information at the beginning, and 20 words with this information at the end. Table 1 shows the success with which subjects were able to correctly identify the word given either the first or the last six letters.

Table 1

Correct identification (percentages) of incomplete words, for the final 40 words selected for use in the battery.

	Information at the beginning of the word	Information at the end of the word
Given word beginning	96.6	9.0
Given word ending	6.1	86.4

When a word is described here as containing its crucial information zone at the beginning, it is meant that it can be identified from its first six letters but not from its last six letters. Similarly, when a word is described as containing its crucial information zone at the end, it can be identified from the last six letters but not from the first six.

Apparatus

The words were displayed on a conventional monochrome TV screen (Helvar Apollo TV-53) and were seen as white against a dark background. Words were displayed using upper case letters. The width of one character was 0.93cm, and with a viewing distance of 62cm one character subtended about 55min of arc. Eye fixations were collected by an Applied Science Laboratories (ASL) Eye-Trac Model 200, which is a spectacle mounted photoelectric recorder. Eye positions were sampled by an Apple 11e microcomputer every 10msec. A chin rest was used to restrict head movements.

Design

The experiment employed a 2 x 2 within-subjects repeated measures design. The factors were information location (beginning/end of a word), and fixation location (beginning/end of a word), and ten words were presented in each of these four conditions.

Procedure

Prior to the presentation of the battery of words, each subject took part in a calibration procedure using the Eye-Trac apparatus and three squares displayed on the TV screen. These squares delineated the maximum horizontal co-ordinates of words used in the experiment, and each square was the size of one character space. The centre square also served as the fixation point in the actual experiment, and was midway between the other two squares. The subjects were asked to fixate the squares in sequence, so that the experimenter could perform an accurate calibration of the Eye-Trac recorder.

A trial in the experiment began by the appearance of the fixation square in the centre of the TV screen. Its location was the same as the third character from the end of a word ("Initial fixation at word ending"), or the same as the third character from the beginning of a word ("Initial fixation at word beginning"). When the subject had been fixating the square for about 100msec it was replaced by the stimulus word. The word which appeared was displayed asymmetrically around the fixation point, with the third letter from the end or the third letter from the beginning coinciding with the fixation point. The word remained visible until the subject pressed a button in order to gain sight of a comparison word which appeared eight character spaces below the first word. The subject's task was to indicate whether the two words were synonyms. The response was given by pressing a "yes" or a "no" button. After an interval of three secs the fixation square reappeared to start the next trial. If minor departures of calibration occurred (indicated by "non-fixation" of the fixation square), the experimenter readjusted the recorder while the subject looked at the square.

Data were collected only from the first word presented on each trial. The synonymity judgement was employed to ensure that subjects read the words for meaning. All 40 trials were presented in one block, with order of presentation randomised. Half of the subjects read a given word with the initial fixation towards its beginning, and the other subjects read this same word when they were given an initial fixation towards its ending.

Prior to the experimental trials, subjects were presented with 10 practice trials each consisting of a word pair discarded from the pilot study of the words eventually selected for the battery.

Results

The eye fixation data from the first fixation upon the word are presented in Table 2, and were subjected to an analysis of variance. The analysis was performed upon the data represented in the two columns of Table 2 which are headed "First

Fixation." This analysis indicated that location of the information zone of the word was not an important factor ($F=3.13$; $df=1,11$; $p>0.1$). The position of the first fixation was potent however ($F=103.85$; $df=1,11$; $p<0.001$), with shorter fixations being associated with the eye initially fixated at the end of the word. The interaction between these two factors failed to reach significance ($F=2.36$; $df=1,11$; $p>0.1$).

Table 2

Mean duration in msecs of the first and second fixations upon the critical word in Experiment 1, as a function of the location of the information zone in the word, and as a function of whether this information was presented to fixation or not.

	Information at the beginning of the word		Information at the end of the word	
	First Fixation	Second Fixation	First Fixation	Second Fixation
Initial fixation at word beginning	289	243	274	215
Initial fixation at word ending	192	237	193	200

The duration of the second fixation was also recorded, and the summed "gaze" of these two fixations on the critical word subjected to an analysis of variance. These are the data in Table 2, with the analysis being performed upon "gaze" durations which were the sum of the first and second fixation durations. The analysis showed the main effect of information location to be reliable here ($F=13.71$; $df=1,11$; $p<0.005$), unlike the analysis which considered the first fixation only. Longer inspections were observed when the information zone was at the beginning of the word. The location of the first fixation was also important ($F=22.27$; $df=1,11$; $p<0.001$), resulting in longer gazes when it was at the beginning of the word. The interaction between these two factors was again unreliable ($F<1$). Because the durations of the first and second fixations were inconsistent with regard to the effects of information location, two further analyses were performed. One analysis investigated the durations of the first and second fixations when the first fixation was positioned at the beginning of the word, and the other analysis considered the positioning of the first fixation at the end of a word.

When the initial fixation was at the beginning of the word, there was no main effect of information location ($F=3.06$; $df=1,11$; $p>0.1$), and the first fixation was reliably longer than the second ($F=8.15$; $df=1,11$; $p<0.02$). There was no interaction between these two factors. When the initial fixation was at the end of the word, the main effect of information location appeared ($F=9.46$; $df=1,11$; $p<0.02$), with longer fixations given to words with their information at the beginning. Although the second fixation tended to be longer than the first, this was not a reliable effect ($F=2.62$; $df=1,11$; $p>0.1$). The interaction between these two factors ($F=12.31$; $df=1,11$; $p<0.005$) indicated that the effect of the longer second fixation was restricted to those cases where the crucial information zone was at the beginning of the word.

Table 3

The mean length of the first saccade (in character spaces) in Experiment 1, as a function of the location of the information in the word, and as a function of whether this information was presented to fixation or not.

	Information at the beginning of the word	Information at the end of the word
Initial fixation at word beginning	2.6	2.9
Initial fixation at word ending	5.3	4.4

The final dependent measure recorded in Experiment 1 was the length of the first saccade, measured in character spaces from the fixation point. These data are presented in Table 3, and were subjected to an analysis of variance. This analysis again indicated the importance of the location of the first fixation (F=94.31; df=1,11; $p<0.001$), this time with longer saccades being associated with the eye initially fixated at the end of the word. The location of the information zone in the word was also indicated as an important factor for this dependent measure (F=16.82; df=1,11; $p<0.02$), although interpretation of this effect is made less simple by the appearance of an interaction between the factors of location of initial fixation and location of crucial information (F=40.60; df=1,11; $p<0.001$). When the eye was initially located at the end of the word, a longer saccade was made if the crucial information was at the beginning of the word than if it was at the end.

Discussion

We can now summarise the main results of Experiment 1, in which subjects were to inspect one word which was presented asymmetrically around the point of fixation, in preparation to performing a synonymity judgement task. The first analysis failed to find any support for the hypothesis that the duration of an eye fixation is sensitive to the location of the information zone within a word (see Table 2). The longest fixations were recorded when the eye initially fixated the beginning of a word, regardless of the location of information. This result is contrary to our prediction that the information zones should attract longer fixations, and although the data tend to confirm the prediction, the statistical analysis just failed to reach significance.

The second analysis concerned the relationship between the durations of the first and second fixations. When the first fixation was at the beginning of the word, there was no effect of the location of the information: whether the information was at the beginning or the end, the first fixation was longer than the second (Table 2). This result also fails to suggest that fixation durations are sensitive to the information being fixated. O'Regan et al (1984) found a longer initial fixation at the beginning of the word only when the information was also at the beginning. Our result differs in that we observed a longer initial fixation at the beginning of the word even when the information was at the end of the word. When the first fixation is at the end of the word, however, our results confirm those of O'Regan: there was a longer second fixation if the information zone was not at the location of the first fixation. This may have represented a rapid rejection of the end of the word and a search for information (in which case the problem is to explain why this only happens when the initial fixation is at the end of the word), or it may have been the operation of O'Regan's non-lexical strategy. This was described as a strategy of "always shift rapidly leftward if you first land on the right" (O'Regan, 1984, p.165), and was offered as an explanation of the appearance of very short initial fixations upon the non-informative ends of words. The explanation was considered implausible because at other times there were longer initial fixations at the (informative) ends of words than at the beginnings. Before rejecting the hypothesis here, we shall also need to present evidence of the existence of lexical influences upon the moment-to-moment variations in fixation patterns.

The length of the first saccade does appear to be sensitive to the location of the information zone (see Table 3). Saccades were longer if the initial fixation was at the end of the word (an attempt to recover the early letters of the word, perhaps), and they were also longer when the information was at the beginning of the word. Importantly, when the initial fixation was at the end, a longer saccade was made if the information was at the beginning of the word than if it was at the end. So, O'Regan's "move left quickly" strategy may have been operating here, but this would not explain why the presence of defining information should attract a longer saccade. Lexical information is affecting eye movements here, but it is not clear whether this is an effect of the attractive influence of non-fixated information, or an effect of the rejection of a non-informative zone of the word. The "attraction" hypothesis suggests that the processing of non-fixated letters informs the eyes that an important zone lies to the left, and the "rejection" hypothesis suggests that it is the realisation that the fixated letters are uninformative that results in a longer saccade. Whereas the attraction hypothesis assumes an influence of parafoveal processing, the rejection hypothesis more simply assumes that processing of fixated material can lead to immediate modifications in saccade programming. We cannot distinguish between these two hypotheses on the basis of the data from Experiment 1.

EXPERIMENT 2: READING WORDS EMBEDDED IN A SENTENCE

Subjects and Apparatus

Twelve Finnish-speaking subjects (four females) were selected from the same population as in the previous experiment. The apparatus was the same as that used previously.

Materials

The critical words used here were those selected by the pilot study and used in Experiment 1, but each word was written into a sentence (4-9 words) with one critical word per sentence. Some of the words were modified by the inflectional changes required by syntax, and so the words in Experiment 2 were 10-16 letters in length. The critical word never occupied the initial position in a sentence. The materials were presented in the form of short stories, with three or four sentences per story. The words were displayed in upper case letters. The presentation of sentences on the TV screen required a greater viewing distance than in Experiment 1, and with a distance of 89cm one character subtended a visual angle of about 37 min of arc.

Design

The experiment used a within-subjects repeated measures design. The factor was information location (beginning/end of the word), and twenty words were used in each of the two conditions.

Procedure

Three squares were again used for the initial calibration: one square in the place of the first character of a line, one in the centre, and one at the end of a line.

A story-trial began when the subject pressed a button. This caused a fixation square to appear at the beginning of a line. After the subject had fixated this square for about 100 msec it was replaced with the first line of the story. After reading this sentence the subject pressed the button to obtain the fixation square and then the next line of the story appeared in the same location. When the presentation of the story had been completed, the subject performed a sentence verification task. This required a "yes" or "no" answer to a question dealing with the general topic of the story. The verification task was followed by re-calibration. Prior to the experiment each subject was presented with three practice stories. Each subject was shown the same material, and subjects were not informed of the significance of the critical words which had been used in Experiment 1.

Results

The durations of the inspections of the critical words are presented in Table 4, with the inspection being described as at the "beginning" of the word if it was in the first half of the word, and at the "end" it it was in the second half. An inspection is used here to describe the total amount of fixation time upon each half of a critical word. These data were subjected to analysis of variance. The factor of location of the information zone was important (F=10.13; df=1,11; $p<0.01$), and although the factor of the location of the inspection was not reliable as a main effect ($F<1$), these two factors produced an interaction (F=22.66; df=1,11; $p<0.001$). Table 4 indicates that the interaction is relatively straightforward: wherever the informative zone was located, there was the longer inspection. When the information zone was at the beginning of the word, the inspection was longer at the beginning than at the end, and when the information zone was at the end, the inspection was longer at the end than at the beginning.

Table 4

Mean inspection duration in msecs upon the critical word in Experiment 2, as a function of the location of the information zone in the word, and as a function of whether the inspection was upon the beginning or the end of the word.

	Information at the beginning of the word	Information at the end of the word
Inspection at word beginning	191	163
Inspection at word ending	172	235

Table 5 presents the number of fixations received by the critical words, again as a function of the location of the crucial information within the word, and of whether the fixations were towards the beginning or the end of the word. These data were subjected to an analysis of variance which indicated that the main effect of information location was unreliable (F=2.74; df=1,11; $p>0.1$), and so was the main effect of location of the fixations ($F<1$), but that there was an interaction between these two factors (F=17.89; df=1,11; $p<0.002$). This suggests that when the crucial information was at the beginning of the word, there were more fixations at the beginning than at the end, and that when the information was at the end, there were more fixations at the end than at the beginning.

The final analysis inspected the position of the first fixation upon the critical word as the sentence was read, as a function of the location of the crucial information within the word. When the informative zone was at the beginning of the word, the first fixation was on average 2.33 character spaces to the left of the centre of the word, and when the informative zone was at the end, the first fixation was 1.68 spaces to the left of centre. This difference was reliable ($F=21.44$; $df=1,11$; $p<0.001$), again suggesting that the location of a fixation is sensitive to the location of lexical information.

Table 5

The mean number of fixations upon the critical word in Experiment 2, as a function of the location of the information zone in the word, and as a function of the location of the fixations.

	Information at the beginning of the word	Information at the end of the word
Fixations at word beginning	1.11	1.01
Fixations at word ending	0.96	1.19

Discussion

The results of the second experiment, in which subjects read sentences containing the critical words scanned in the first experiment, provide clearer support for the hypothesis that the information being fixated can exert moment-to-moment control over the pattern of eye fixations.

The total inspection duration depended upon whether it was upon the information zone or not (see Table 4). When the information was at the beginning of the word inspections at the beginning were longer than inspections at the end, and when the information was at the end of the word inspections at the end lasted longer than inspections in the "wrong" zone. This shows a clear effect of the information zone within a word influencing the amount of attention given to that zone.

The location of the information zone also influenced the number of fixations upon the critical word (see Table 5). If the information zone was at the beginning there were more fixations at the beginning of the word, and if the information was at the end there were more fixations at the end. The location of the first fixation was also nearer to the beginning of the word when the information was at the beginning rather than at the end. Dunn-Rankin (1978), Rayner (1979), and Kliegl, Olson and Davidson (1983) have also commented upon the tendency for the fixation to be on the left of the word's centre.

The results from the sentence comprehension experiment give good support to the hypothesis which suggests that eye movements are under the moment-to-moment control of the information being currently processed. The duration of inspections varied according to whether it was the information zone that was being fixated, and this effect held whether it was the beginning or the end of the word that was fixated. The symmetry of this effect means that O'Regan's (1984) non-lexical "always move left" strategy was not responsible for the pattern of results found here. The location of the fixations also tended to be towards the informative part of the word, again supporting the notion of ongoing processing having an immediate effect upon fixation behaviour, but this result also supports the stronger "attraction" hypothesis. By this view, eye fixations are attracted to informative or interesting locations in the text, and so these locations should receive an increased number of fixations. This hypothesis is confirmed: the informative zones of the words used in this experiment received more initial fixations than the non-informative zones, independently of whether these zones were located at the beginning or the end of the word. Furthermore, the location of the information zone influenced the position of the first fixation upon the word, with the fixation being further to the end of the word when the information was at the end. The only reason to suppose that the information zones should attract eye fixations is if we assume that the eye guidance system has knowledge of their informativeness prior to their fixation.

CONCLUSIONS

There are a number of factors which can influence the duration and location of an eye fixation during reading, and the present experiments have identified a preferred viewing position within a word, and the importance of the location of information within a word. Factors not considered here include syntactic constraints, position within a sentence, and semantic saliency, for example, and so our conclusions are based upon a very restricted view of the process of eye guidance during reading.

In Experiment 1 the isolated words attracted longer fixations at the beginning of the word, and an initial fixation at the end of the word tended to be brief and followed by a longer fixation at the beginning. This is similar to the "beginning dominance" reported by O'Regan (1984). A related effect was also observed in the sentence comprehension experiment, in which the first fixation tended to be to the left of the centre of the word.

The synonym experiment reported here provided little evidence of the importance of information zone location for the moment-to-moment control of fixation. Fixation duration did not increase as the information content increased, except when the reader's first fixation was at the end of the word. In this case there was a longer second fixation if the information zone was at the beginning than at the end, where the eye had first dwelt. This shows sensitivity to the distribution of information within a word, but leaves us to explain why the pattern is only observed when the first fixation is at the end of the word. Fixation location also varied according to the location of the information, but again the effect depended upon an initial fixation at the end of the word. When the eye first fixated a non-informative end of a word there was a longer saccade in the direction of the beginning of the word, than when the information had been at the end. The spatial distribution of the word seems to be at least as potent a factor as information distribution, in this experiment.

The sentence comprehension experiment provided much clearer evidence of the influence of information upon the moment-to-moment control of eye guidance. In this experiment the reader was not presented with the initial fixation at the beginning or the end of the word, but was able to select the location of fixation, and indeed choose to not fixate upon the word at all. (As the words were long, this rarely happened.) Longer fixation durations were recorded at the beginning of a word when the word contained an information zone at the beginning, and longer fixations were recorded at the end for those words containing the information zone at the end. This shows that fixations can be influenced by the information being fixated. The location of the fixation within a word was also affected by the location of the information. When the information was at the beginning, there were more fixations at the beginning, and when the information was at the end, there were more fixations at the end. Similarly, the first fixation was nearer to the end of the word when the information was at the end. This shows that fixations can also be influenced by information ahead of fixation. It is not clear whether this is orthographic or lexical information: it may be the case that highly familiar orthographic patterns within words result in saccades which tend to avoid these patterns, or it may be that lexical information about the component morphemes can act to guide fixations. Whether the controlling information is orthographic or lexical, however, the non-fixated information zone is able to affect the location of the next fixation, in agreement with the hypothesis that parafoveal processing can be used by the mechanism which decides where we should look next.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

EYE MOVEMENTS IN APHASIA DURING LEXICAL PROBLEM SOLVING

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Duration, frequency and alternation of gaze of aphasic and control subjects were recorded during a lexical-semantic analogy task. A subgroup of aphasics avoided the task demands by relying only on intra-conceptual processing. Another subgroup exhibited very much the same eye movement pattern as the normal controls. They undertook inter-conceptual processing. Nevertheless, they gave significantly fewer correct responses, i.e. they exhibited disturbances in semantic integration, while the stepwise semantic decisions that guide eye movements during lexical problem solving were intact.

INTRODUCTION

Studies on linguistic errors in visual matching tasks have demonstrated that semantic comparisons across concepts are outstandingly difficult in aphasia. For example, aphasic patients frequently fail when they have to recognize a common property of objects, e.g. 'white' common to 'snowman' and 'swan' (cf. Cohen, Glöckner, Lutz, Maier, Meier, 1983).

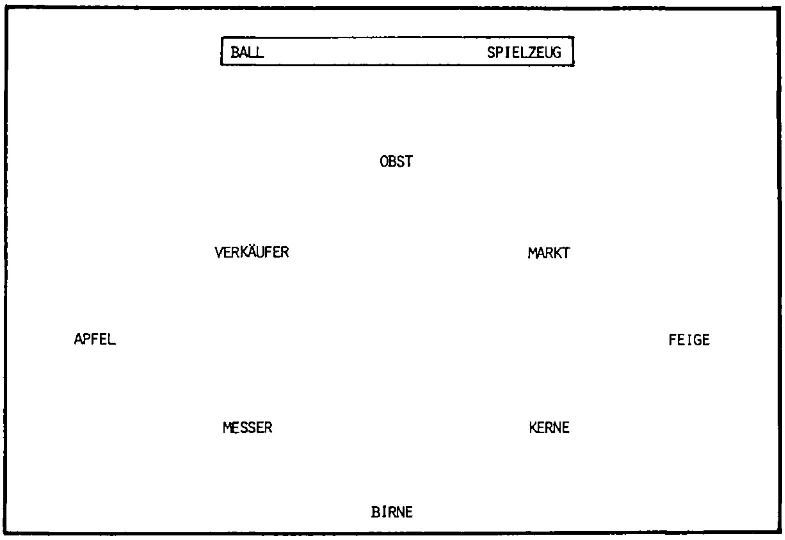
The underlying mechanisms for this failure could be twofold:
1) Comparisons across concepts are per se impossible. Therefore, patients resort to intra-conceptual processing alone or even to pure guessing.
2) Inter-conceptual processing is undertaken, but cannot be successfully accomplished.

To study these assumptions, we developed a visual multiple-choice matching task, during which we registered the eye movements of the subjects. Their duration, frequencies and alternations of gaze may indicate what the underlying mental processes are that lead to a correct or erroneous response.

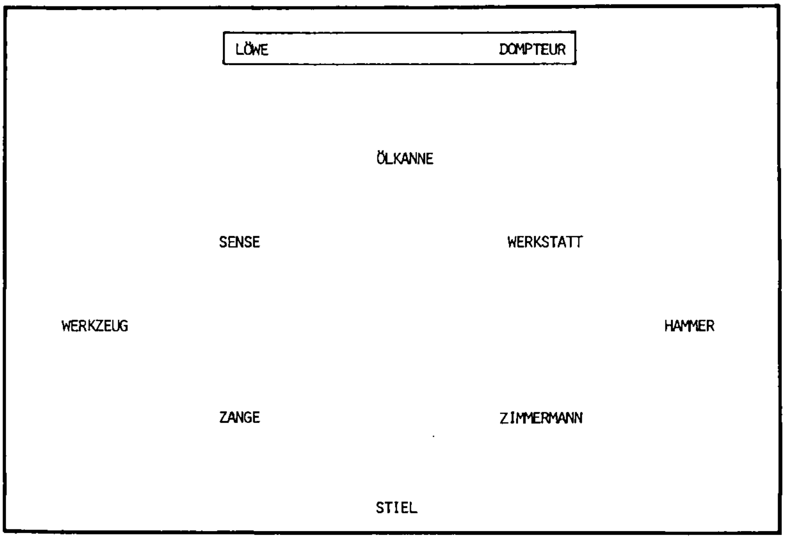
METHODS

1. Semantic analogy task

Subjects are shown a pair of words and are asked to select from a multiple-choice set two other words that convey the same semantic relation as the two reference words (cf. figure 1).



Reference relation superordination: Ball - Spielzeug (toys)
Target word: Obst (fruit)
Possible target associates, high: Apfel, Birne (apple, pear), low: Feige (fig)
Distractors: Kerne, Markt, Verkäufer, Messer (core, market, seller, knife)



Reference relation object - person: Löwe - Dompteur (lion - tamer)
Target word: Zimmermann (carpenter)
Possible target associates, high: Hammer, Zange (pliers), low: Werkzeug (tool)
Distractors: Sense, Stiel, Werkstatt, Ölkanne (scythe, handle, workshop, oil can)

Figure 1
Examples of stimuli

The task allowed for at least three strategies of problem solving:

1. After comparing the two reference words, the subject would search for an analogous pair among the multiple choice set.
2. Each reference word is individually compared with all words of the multiple choice set until a semantically similar word is found.
3. Only the multiple-choice set is searched through for a particular semantic relation or category that the subject has recognized to recur from one task item to the other.

In contrast to the optimal strategy 1, strategies 2 and 3 would increasingly reduce the task demands. Strategy 3 would indicate intraconceptual processing, which is perseverated across items.

2. Material and Procedure

In constructing the items, the following seven semantic categories of target words were considered: superordinate (3 x), typical coordinate (2 x), untypical coordinate (2 x), part (2 x), location (2 x), person (2 x), and associated object (2 x). There was a total of 15 items, with the lexical content of reference and multiple choice words systematically varied. However, each multiple choice set contained the same semantic categories.

The items were presented in three blocks of five items each. Before each block all stimulus words were shown individually to the subject together with the depiction of their meaning. Thereby, we tried to reduce aphasic difficulties in reading and/or comprehension of words. Eye movements of subjects were registered during scanning of the multiple choice sets. When the subject was sure about the solution, he gave a sign. He then would look at the two words selected, which was likewise observed on the video control monitor. Thus, the aphasic patients could give their solutions without speaking.

3. Eye movement registration

Method: Point of regard measurement, tracking of corneal reflection center with respect to the pupil center (infrared light technique).

Apparatus: DEBIC 84, digital computer, conventional video system (eye and scene camera), slide projection - sampling rate 25 - 50/sec, accuracy (euclidian) $\bar{x}$ = .07 degrees, s = 1.6 degrees (based on 2721 fixations of 18 students on a 20 point-grid).

Experimental setting and procedure: Head fixation of subjects, 175cm viewing distance, projection screen 75cm high by 100cm wide (24 degrees by 32 degrees visual angle), calibration immediately before recording (20 lightpoints regularly distributed on the screen), online processing of point of regard and control on video monitor.

Method of evaluation: Data reduction by modified version of EMAN (Kliegl, 1981), duration of relevant fixations (= 'gaze') > 100msec, elliptical areas of gaze around center of stimulus words.

Subjects

The sample characteristics are given in table 1. The distinction of two aphasic groups is a result of this study. Patients with 'perseveration' selected outstandingly often words of the same semantic category. They did so in at least 8 of the 15 items. In each patient, this exceeded significantly the frequencies found in the non-aphasic groups.

GROUPS	N	SEX F	M	AGE YRS MD	RANGE	DURATION MTHS MD	RANGE
STUDENTS	11	3	8	28	23-36	-	-
NORMAL CONTROLS	11	5	6	44	32-58	-	-
CNS-PATIENT WITHOUT APHASIA	8	3	5	47.5	35-62	-	-
APHASIC WITHOUT CATEGORY PERSEV	10[1]	3	7	48.5	42-58	24.5	1 - 85
APHASIC WITH CATEGORY PERSEV	7[2]	5	2	50	29-71	17	12 - 108

[1] 4 Broca, 1 Global, 1 Wernicke, 2 Non-Class, 2 Non-Stand.
[2] 3 Broca, 2 Wernicke, 1 Amnesic, 1 Non-Class

Table 1
Sample characteristics

RESULTS AND CONCLUSIONS

1. Responses: Preceding gaze duration and frequency

First, we computed how long and how often multiple choice words were looked at during solving of the task. We distinguished between response words, i.e. words that were eventually given as a solution as opposed to nonresponse words (cf. table 2).

GAZE DURATION msec gaze frequency f per word x(s)		RESPONSE WORD	NON-RESPONSE WORD	simple main-effect p-value
STUDENTS	msec	847 (453)	567 (315)	.0308
	f	2.6 (1.0)	1.8 (0.8)	.0006
NORMAL CONTROLS	msec	1425 (668)	761 (447)	.0000
	f	3.7 (1.3)	2.1 (0.9)	.0000
CNS-PATIENTS WITHOUT APHASIA	msec	1571 (878)	753 (456)	.0000
	f	4.1 (1.8)	2.2 (1.1)	.0000
APHASICS WITHOUT CATEGORY PERSEV	msec	4160 (1272)	1893 (822)	.0000
	f	6.7 (2.8)	3.5 (1.8)	.0000
APHASICS WITH CATEGORY PERSEV	msec	3148 (846)	1528 (672)	.0000
	f	6.6 (1.7)	3.8 (1.8)	.0000
group differences	msec	.0000	.0000	ANOVA
simple ME, p-value	f	.0000	.0000	split-plot design

Table 2
Processing of response vs non-response words

As expected, significantly higher gaze values were always found for response words. Thus, gaze duration and frequency indeed reflected what was going on in the subjects' minds.

Both aphasic groups needed significantly longer for scanning than any of the non-aphasic groups. The aphasics with perseveration were only slightly faster. Their perseverations in responding did not exempt them from full intra-conceptual processing which was obviously demanding enough.

2. Responses: Preceding gaze alternations

The proportions of alternations involving response words (R) were always significantly higher than chance (cf. table 3). This was also true for alternations between two reference words (REF), but not in the group of aphasics with perseverations. They indeed relied primarily on strategy 3, i.e. on intra-conceptual processing of the multiple-choice words, irrespectively of the reference words given.

	GAZE ALTERNATIONS						
means	R-R	R-N	N-N	REF-REF	REF-R	REF-N	TOTAL
CHANCE PROPORTION	2.2%	26.7%	33.3%	2.2%	8.9%	26.7%	100%
STUDENTS	0.9^+ (5.9%)	6.2^+ (39.9%)	5.8^+ (37.6%)	0.6^+ (4.0%)	0.8^- (4.9%)	1.2^- (7.8%)	15.5%
NORMAL CONTROLS	1.9^+ (9.4%)	8.0^+ (40.0%)	6.6 (33.2%)	0.7^+ (3.5%)	1.3^- (6.6%)	1.5^- (7.4%)	20.0
CNS-PATIENTS WITHOUT APHASIA	2.8^+ (12.7%)	8.3^+ (37.9%)	7.3 (33.2%)	1.0^+ (4.7%)	1.0^- (4.8%)	1.5^- (6.8%)	21.9
APHASICS WITHOUT CATEGORY PERSEV	4.2^+ (12.1%)	12.5^+ (35.7%)	11.2 (31.9%)	1.1^+ (3.2%)	2.6^- (7.4%)	3.4^- (9.7%)	35.0
APHASICS WITH CATEGORY PERSEV	2.5^+ (10.4%)	9.2^+ (38.5%)	8.9^+ (37.3%)	0.3^- (1.5%)	1.1^- (4.7%)	1.8^- (7.6%)	23.8

$^+$significantly more frequent than chance

$^-$significantly less frequent than chance (binomial distribution, cf. Sachs,1972)

Table 3
Comparisons between response (R), non-response (N) and reference words (REF)

Most interestingly, in all groups, the proportions for alternations between a reference word and a multiple choice word were always lower than chance (cf. table 3). This indicates that strategy 2, which would require such comparisons, did not play an important role. Rather, aphasics without perseverations just as the non-aphasic groups appear as having relied on the optimal strategy 1. They indeed performed as required by an analogy task: They tried to comprehend the semantic relation between the reference words and to find an analogous relation among the multiple choice words.

3. Targets: Accuracy, gaze duration and frequency

Choosing a strategy that is optimal for the demands of the task did nevertheless not in all groups lead to a successful solution. Both aphasics without perseverations and CNS-control patients selected significantly less often the target word than students and normal controls (cf. tabel 4). Correspondingly, students and normal controls looked significantly longer and more often at the target words than at distractor words.

$\bar{X}$ s	CORRECT TARGETS max=15	GAZE DURATION (msec) per TARGET	GAZE DURATION (msec) per DISTRACTOR	simple ME p-value	GAZE FREQUENCY per TARGET	GAZE FREQUENCY per DISTRACTOR	simple ME p-value
STUDENTS	13.6 1.1	847 666	564 312	.000*	2.6 1.6	1.7 0.8	.002*
NORMAL CONTROLS	12.5 1.3	1354 959	811 450	.000*	3.4 2.1	2.2 0.9	.000*
CNS-PATIENTS WITHOUT APHASIA	7.4 2.0	1198 979	879 577	.032	3.2 2.0	2.5 1.2	.051
APHASICS WITHOUT CATEGORY PERSEV	6.0 2.2	3201 2441	2099 1379	.002*	5.0 4.2	3.8 2.5	.025(*)

*Significant difference, split-plot ANOVA, sequentially rejective multiple test procedure, Holm (1979)

Table 4
Processing of target vs distractor words

Quite surprisingly, the gaze values revealed that the aphasic patients also showed preference for the target word despite the poor accuracy of their solutions. This parallels earlier findings (cf. Lass, Huber, Lüer, 1984, Huber, Lüer, Lass, 1986). Aphasia apparently affects the 'assembling functions' in linguistic problem solving, while the detection of individual linguistic features - as controlled via the visual system - seems to be better preserved.

4. Targets: Influence of semantic category

In table 5 the gaze values of normal controls and the aphasic subjects without perseveration of semantic category in their responses are given for two classificatory categories (superordination and typical coordination) and two thematic ones (location and person).

Our interpretation is based on the following assumptions:

1) Values for gaze duration and/or frequency reflect concern with a possible solution.
2) Distribution of gaze alternations may reflect two combination strategies:
   -inclusion if $T \leftrightarrow A \ngtr T \leftrightarrow D$, $D \leftrightarrow D$
   -exclusion if $T \leftrightarrow D > D \leftrightarrow D$

means		ACCURACY TARGET CORRECT	GAZE VALUES PER WORD DURATION (sec) T	A	D	FREQUENCY (f) T	A	D	ALTERNATION (f) T↔A	T↔D	D↔D
SUPER ORDINATE	NORM	85%	0.9	0.7	0.7	2.4	2.1	2.0	0.3	0.7	0.3
	APH	50%	3.7	2.3	2.3	5.0	4.0	4.2	0.8	1.4	0.8
TYPICAL COORDINATE	NORM	91%	1.1	0.9	0.4	2.7	2.5	1.4	1.1	0.4	0.2
	APH	75%	2.6	2.4	2.0	4.4	4.2	3.6	1.0	0.8	0.5
LOCATION	NORM	86%	1.4	0.9	0.7	3.6	2.6	2.0	0.8	0.9	0.3
	APH	40%	2.5	3.0	1.7	4.3	5.0	3.2	1.0	1.0	0.5
PERSON	NORM	91%	2.0	1.2	1.3	5.1	3.1	3.3	1.4	1.1	0.7
	APH	60%	4.8	2.9	2.6	8.1	5.5	5.1	2.5	1.7	1.0

NORM = normal controls (n = 11), APH = aphasics without category persev. (n=10)
T = target, A = high target associates, D = distractors
Results from t-tests: no underlining indicates significant difference with Holm's test procedure, dotted underlining indicates significant difference for alpha = 5%, solid underlining indicates no significance.

Table 5
Processing of different semantic categories

The gaze patterns clearly revealed a different influence of each semantic category. Superordinations required exclusions. The aphasics paid most of their attention to the target. Typical coordinations were easy even for the aphasics, but their gazes do not tell what was going on. Normal controls relied solely on inclusions and they were primarily concerned with both target and associates. Locations and persons were figured out by aphasics and normal controls much in the same way. Combination was always done via inclusion and exclusion. With location, both groups attended to target and associates, with person only to the target. Probably these categories are processed (not solved!) as well by the aphasics because they involve ontological as opposed to classificatory knowledge.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

TYPOGRAPHICAL CHARACTERISTICS AND READING

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In a previous study with children (Heller & Heinisch 1985) we found definite effects of letter size and letter spacing on eye movement parameters. These effects, however, do not fit one of the usual models. Since this could be due to the low reading skills of our subjects we proceded to carry out similar experiments with adult readers. In this study letter size and letter spacing were separately varied. The texts consisted of meaningful words of about 10 letters in random order. Eye movement parameters were registered electrooculographically. Effects were found on the number and duration of fixations as well as on the saccade size measured in letter positions.

INTRODUCTION

Since the time when modern experimental reading research was founded by Emile Javal, a French mining engineer, ophtalmologist and first director of the Sorbonne ophthalmological laboratory, the question of typographical characteristics and eye movements has received attention. As early as 1878 Javal's "Essai sur la physiologie de la lecture" (1878, 1879) dealt thoroughly with this question and his student Lamare developed the first equipment for eye movement registration at this time (published, however, only in 1893). Javal himself had done eye movement observations using afterimages, a technique presumedly inspired by his translation of Helmholtz' Physiological Optics.

In spite of the long tradition, research in this area has left open many questions. This is true despite the fact that Tinker's half-century of investigation covered nearly all the questions that can be raised in connection with the "Legibility of Print" (1963). Summarizing the earlier research in this field and particularly the work of Tinker and his coworkers, O'Regan, Levy-Schoen & Jacobs (1983, p. 457) comment very briefly: "...these authors' purpose was to find the optimal conditions for reading, and not the reason why these conditions were optimal." This becomes especially obvious in connection with recent problems in designing and evaluating the typographic layout of screen texts (O'Regan & Levy-Schoen 1983, O'Regan, Levy-Schoen, Humbert, Jacobs & Coëffé 1984, Groner & Heller 1985). Regarding the sometimes astonishing difficulties encountered in reading certain display texts it seems most reasonable to assume - besides possible special technical problems - that this is associated with as yet unresolved difficulties in determining quantitative criteria of legibility in relation to typographical characteristics.

We can postulate two possible reasons for this: a substantial and a methodological cause:

1. The reading process is highly practiced and from this stems a certain flexibility (demonstrated for example by Levy-Schoen, 1980). This enables skilled readers to adapt - at least temporarily - to different even sub-optimal typographical conditions. The rather weak and partly inconsistent effects often found in such studies could be attributed to this. Furthermore, it can sometimes be difficult to separate the typographical influences in a study from other variables such as comprehension requirements which may affect the results to a greater extent.

2. The main instruments of reading research, eye movement registration and tachistoscope experiments,lead (each for different reasons) to results which cannot easily be generalized with regard to the effects of typographical factors in reading.

With the tachistoscope it is possible to show relations between identification time and even small differences in letter characteristics. But this leads only to letter confusion matrices or to identification rules of single words without any context. Process variables of reading, however, are excluded to a large extent. The question of whether reading a text is fatiguing or strenuous can rarely be predicted form such experiments. In contrast, eye movement registration is sensitive to such variables. The problem here is that the relevant parameters e. g. fixation duration, saccade size and number are hampered by high intra- and interindividual variance. Certainly this results mostly from interactions of these parameters with the reading skills of the subjects and pecularities of the texts read. In addition there are interactions between the experimenter and the more or less complex registration systems. Finally different computer programs and identification algorithms for saccades and fixations were used; this is a further source of variance which should not be underestimated. In all this variance which we were producing together with our subjects and our experimental equipment it might happen that the possible weak effects of typographical variations occasionally get lost.

The "persisting vigour" of typographical questions in reading research is as astonishing as the fact that the theoretical positions being discussed in this connection have not changed during all this time. The significance of the "Gesamtform" (word shape) in reading pointed out for the first time by Erdmann & Dodge (1898) is still discussed. In this context the different versions of the global-to-local models play an important role. Many recent papers can be centered around this theory actually initiated by Bouma (1971). For example Keren & Baggen (1981) belongs here, as well as the findings of Haber & Haber (1981) which indicate that some common English words can be identified from their silhouettes, i. e. by the outline given by the characteristic combinations of ascending and descending letters within a word; furthermore the dispute between Navon (1981) and Miller (1981) which Navon clothes in the metaphorical question "forest before trees?", must be seen in this framework. The question of simultaneity versus succession is here disguised, a problem which in respect to reading had already been discussed by E. H. Weber (1846).

The opposite position to the word shape theories is represented by the different analysis-by-synthesis models. In these, reading is interpreted as an accumulation process of the visual system, based on a more or less fixed feature list (Rumelhart & Siple 1974). Many arguments brought forth in this context can already be found in an article by Goldscheider & Müller (1893), who tried to show that letters and words are identified by their constituting elements (lines, hooks, circular arches etc.). From the point of view of eye movement research, however, the confrontation of word shape with feature accumulation as well as that of simultaneity with succession is not particularly useful. Here we have a clear hierarchical structure: Inasmuch as it is appropriate to consider isolated saccades (leading from one word to another), these can only be interpreted as guided by word shape which bring the eye to a position where local features can be perceived. As to this point of view, the dispute reflects more methodological than content-oriented problems in reading: The tachistoscope stresses "static" word identification with its feature lists while eye movement registration focuses more on word shape and on dynamic aspects of the reading process.

But before the obviously needed integrative models can be formulated, it is, however, necessary to do further eye movement research aiming at paradigms in which typographical effects can be shown clearly and replicated, such that predictions derived from such a model become proveable. We believe we have an experimental setup which is suitable for revealing such effects. It consists of an EOG registration system (Heller 1976, 1983) and different texts constructed in a special way: In order to make them equally difficult, meaningful words of a certain length were arranged in random order and embedded in a meaningful context (Heinisch 1984). An example used in the presented study is:

> "Today you will have to write a composition using the following words: observation, dauntless, landslide, successful, authoress, hindbrain, relaxation, exhibiting...
> You should use all these words and try to make a good story."

Eye movement data were collected only from the lines with the randomly ordered words. This way the variance resulting from the contents of the read text was reduced to a relative minimum and a real reading task was maintained.

With such texts we have previously shown that in children aged 7 to 10, increasing letter spacing had a greater facilitating effect on reading performance than increasing the letter size; furthermore we demonstrated that within the given range, words written in small letters were easier to read then those wirtten in larger letters (Heller & Heinisch 1985). In the following experiments the effect of letter spacing and letter size is investigated separately, with skilled (adult) readers.

EFFECTS OF LETTER SPACING

Based on present knowledge, at least four hypotheses can be stated concerning the effects of letter spacing on eye movements:

1. Although Tinker did not investigate separately the factor letter spacing, his research on typographical variations (Tinker 1958, 1963, Tinker & Paterson 1955, Paterson & Tinker 1940, 1947) lead one to expect that non-optimal print (too small or too large letter spacing) should give rise to more fixations and longer fixation durations; that is, in his terms, a smaller perceptual span (words per fixation)

and an increased perception time (fixation frequency multiplied by fixation duration). These findings lead one to expect that in the present study the functions relating eye movement parameters to typographical variations should be curvilinear with a maximum.

2. According to McConkie & Rayner (e.g. 1975) increasing letter spacing should lead to decreased fixation durations because less information would be accessible within the visual span.

3. It can further be expected that short fixations should lead to an increased number of fixations (and saccades).

4. Concerning saccade sizes measured in letter spaces, one could expect, according to these authors, that if letter spacing gets wider, saccade size should decrease because fewer letters can be preprocessed in the peripheral vision.

SUBJECTS AND MATERIAL

16 students from different university departments participated as subjects. Eye movements were registered electro-oculographically with ZAK-Instruments amplifiers interfaced to a modified Kontron microcomputer (128 K dyn. RAM), sampling rate was 100/s; the resolution was about .3° (further details of the registration system can be found in Heller 1983). The texts were constructed as described above and written with a typewriter. The critical lines consisted of 30 words in total with an average number of ten letters. Four different letter spacings were used. The length of lines was always 15 cm = 27.72° visual angle; the reading distance was 31 cm. In order to realize a completely balanced split-plot design each text existed in each spacing version and all subjects read texts in all given letter spacings.

The following lines show an example of the different texts (reduced to about 75 percent of its original size), and Table 1 summarizes the data of the reading material.

1 *blätterpilz, Desinfektion, Schwangerschafts-*
beratung, Flamingo, Badezimmer, Ausbildungs-

2 *angelegenheit, Fusspilz, Gummiboot, Weiberheld, ineinander-*
schieben, momentan, faulenzen, Schmetterling, Wirtschafts-

3 *anweisung, Bekämpfung, Insekten, kritisch, Autorin, Telefonbenützungs-*
gebühren, Gedanken, Kochtopf, verloren, Zollabfertigung, Kriegsdienst-

4 *Maulwurfsgrille, angeklagt, bedingungslos, Zwetschgenbaum, Schrebergarten, Kurzschluss-*
handlung, halleluja, gefährlich, Trickfilm, Literatur, Vormittag, seekrank, Vorlesungs-

Table 1:

Characteristics of the texts used. Text 1 = wide letter spacing. The distance between the letters is measured in two ways: From the middle of a letter to the middle of the next letter = distance a; and from the end of a letter to the beginning of the next letter = distance b (In text 4 distance b could not be measured because most letters touched each other).

text No.		1	2	3	4
average letters per word		10	10	10	10
average word length in cm		3.33	2.50	2.00	1.67
average word length in degrees		6.15	4.62	3.69	3.08
distance a in mm		3.50	3.00	2.50	2.00
distance b in mm	$\bar{X}$	2.25	1.40	.93	-
	s	.21	.18	.26	

The instruction was to read silently. All subjects had been familiarized with the experimental setup in a preexperimental session completely identical with the main experiment except for the texts (they were, however, constructed in the same way as in the main experiment).

RESULTS

Data reduction was done with a semi-automatic interactive identification program (see Heller 1983).

Table 2 shows the means and standard deviations of the different eye movement parameters.

Table 2:

Eye movement parameters in reading 30 randomly ordered words of average length 10 letters; means from 16 subjects; 1 = wide letter spacing, 4 = narrow letter spacing.

text No.		1	2	3	4
number of fixations	$\bar{X}$	58.00	50.44	46.25	45.00
	s	13.65	10.18	8.40	8.08
fixation duration ms	$\bar{X}$	233.40	254.20	273.30	301.60
	s	27.70	28.60	34.70	35.10
number of progressions	$\bar{X}$	45.44	40.88	38.88	37.75
	s	10.76	8.20	7.38	6.54
progression size in letter positions	$\bar{X}$	7.54	8.61	9.50	9.71
	s	1.50	1.73	1.91	1.95
number of regressions	$\bar{X}$	4.56	3.56	2.38	3.25
	s	4.26	3.65	2.30	2.32
regression size in letter positions	$\bar{X}$	2.79	3.90	4.28	6.04
	s	.83	1.41	1.30	2.08
line return sweep in degrees	$\bar{X}$	24.34	25.28	25.50	26.03
	s	3.34	3.40	3.23	3.01
total reading time	$\bar{X}$	13.73	12.87	12.63	13.53
	s	4.65	3.32	2.84	2.69

Figures 1 - 3 show the major eye movement parameters as a function of letter spacing (1 = wide spacing). The error bars represent $\frac{\sigma}{\sqrt{N}}$.

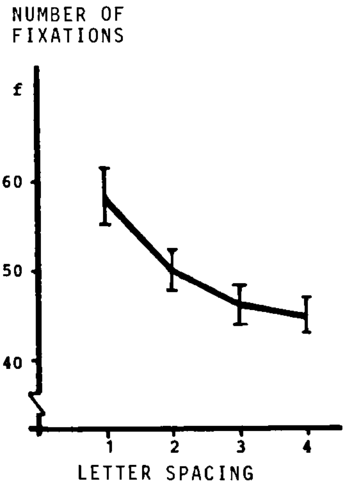


Figure 1
Total number of fixations for 30 words as a function of letter spacing,
1 = wide, 4 = narrow

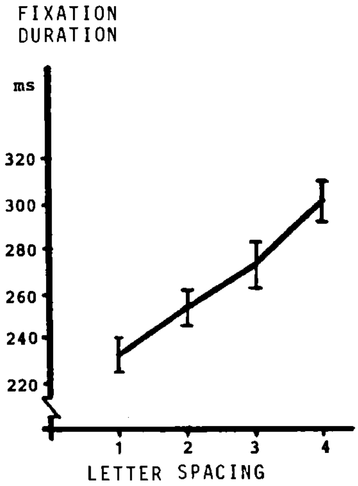


Figure 2
Average fixation duration as a function of letter spacing,
1 = wide, 4 = narrow

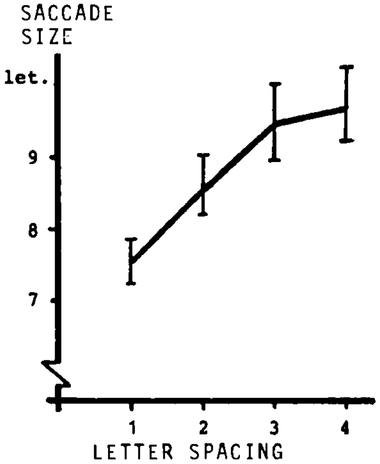


Figure 3
Average size of progressions measured in letter positions as a function of letter spacing,
1 = wide, 4 = narrow

The differences shown in Figs. 1 - 3 between letter spacings are significant ($p < .01$). This means that the narrower the spacings between the letters, the smaller the number of the fixations and the shorter the fixation duration is; i.e. wide letter spacings produce a reading process which is characterized by many short fixations. This fits hypotheses 2 and 3. Saccade size corresponds to this result. Words written in narrow letter spacings were read with larger saccades, i.e. more letters were bridged by each saccade and the text was processed in larger units. Hypothesis 1 formulated according to Tinker's results is not supported by the observed data.

In sum it can be said: Even though the text with the narrowest letter spacings is perceived as being more difficult to read, subjects nevertheless process it more "economically" from an oculomotorical point of view, that is with larger saccades and longer fixations.

If one looks at the total reading time shown in Figure 4 a new question arises.

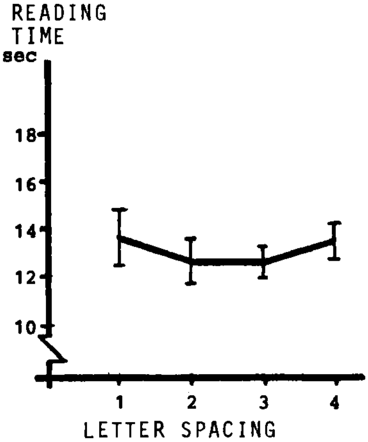


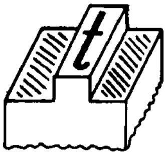
Figure 4
Total reading time for 30 words
as a function of letter spacing,
1 = wide, 4 = narrow

There is no difference in total reading time for the different letter spacings. This is in contrast to Tinker (1963) who stated that total reading time is the best indicator of legibility depending on typographical variation.

Given the relatively constant reading time, it can be argued that the narrowest typeface is read with the longest "true" processing time, since fewer saccades are used, and so a smaller percentage of the total time is spent programming eye movements. This may indicate that the narrow type face is also the most difficult to read. But ultimately this question can only be decided with the aid of ratings.

EFFECTS OF LETTER SIZE

In contrast to the factor letter spacing this typographical variation was investigated by Tinker & Paterson (1955), but with remarkable difference to our experiment reported below: They used printed texts in 6, 8, 10, 12 and 14 point type size with 19-pica line width of different type faces such as Granjon, Scotch Roman (Tinker 1963, p. 70). This way letter spacing remained uncontrolled because in



each type size (of the same type face) a letter occupies a fixed proportion of the total area of the key (as illustrated with bars in the figure beside). This is individually determined for each single letter and each type size by the designer of a type face, because a proportional enlargement of a type set would lead occasionally to "holes" within the print. The fact that the determination of letter spacing is still an art of type face designing indicates that there is a lack of knowledge about psychophysical functions of the relation of letter size and letter spacing.

According to Tinker & Paterson's results it could be expected that fixation frequency for smaller and larger type size should be higher than for a medium letter size. The same is predicted concerning reading time and regression frequency, whereas fixation duration should decrease with increasing letter size.

With regard to the saccades size measured in letter positions O'Regan's (1981) "grain model" predicts that it should not be affected by the different letter sizes because the "grain" is mostly determined by the type font which does not vary in our study. As shown by O'Regan, Levy-Schoen & Jacobs (1983) the different viewing distances in reading (30 - 120 cm) do not affect saccade size providing the letters are clearly separated, that is there is a blank between each letter: "Normal" spaces between the letters with increasing distances possibly lead to a slightly reduced number of letters skipped by an average progression (however, a nonsignificant effect) and to a significant increase of fixation duration. If decreasing the letter size (in the given range) is equal to increasing the viewing distance the following experiment should profess to this.

SUBJECTS AND MATERIAL

The procedure was exactly the same as described in the letter spacing experiment above. Subjects were 16 students of different university departments. The following lines show an example of the different texts, and Table 3 summarizes the data of the reading material. The letter size variation was realized photographically.

1 ***anweisung, Bekämpfung, Insekten, kritisch, Autorin, Telefonbenützungs-***
gebühren, Gedanken, Kochtopf, verloren, Zollabfertigung, Kriegsdienst-

2 ***Unterhose, Gegenargument, bestanden, Waschmittel, Seehundbaby, Bühnen-***
anweisung, Bekämpfung, Insekten, kritisch, Autorin, Telefonbenützungs-

3 ***schauspieler, Bekleidung, zahlreich, Souvenir, hervorragend, menschen-***
freundlich, Gummiboot, Fusspilz, lebensgefährlich, Bazillen, Familien-

4 ***freundlich, Gummiboot, Fusspilz, lebensgefährlich, Bazillen, Familien-***
angelegenheit, Programm, Drahtbürste, momentan, Infektion, ineinander-

Table 3.:

Data of the used texts. Text 1 = large letter size, text 4 = small letter size. Distance a = between the middle of two letters. Distance b = between the end of a letter and the beginning of the next letter.

text No.	1	2	3	4
average letters per word	10	10	10	10
average word length in cm	2.35	2.13	1.92	1.72
average word length in degrees	4.34	3.94	3.55	3.18
distance a in mm	2.41	2.18	1.97	1.75
distance a in degrees	.446	.405	.364	.323
distance b in mm	1.06	.96	.87	.77
line length in degrees	31.20	28.31	25.47	22.62

RESULTS

Data reduction here in comparison to the first experiment was somewhat different. Because increasing line length leads to corrective saccades following the line return sweep (Heller 1982) the first saccade in a line was skipped, whenever it was a regression and the preceeding fixation duration was <120 ms.

The following Table 4 and Figures 5 - 8 show the major eye movement parameters. The error bars represent $\frac{\sigma}{\sqrt{N}}$.

Table 4:

Eye movement parameters in reading 30 randomly ordered words of an average length of 10 letters in different letter sizes; text 1 = large letter size; means from 16 subjects

text No.		1	2	3	4
number of fixations	$\bar{X}$	42.31	41.13	40.44	39.31
	s	6.19	7.88	5.72	6.53
fixation duration in ms	$\bar{X}$	265.8	270.6	277.4	293.5
	s	34.6	37.8	33.8	50.6
number of progressions	$\bar{X}$	36.44	35.38	34.50	33.19
	s	6.12	7.48	5.42	6.31
progression size measured in letter positions	$\bar{X}$	8.98	9.54	9.31	9.73
	s	1.28	1.59	1.50	1.50
number of regressions	$\bar{X}$	.88	.88	.94	1.13
	s	1.26	1.09	1.06	.89
regression size measured in letter positions	$\bar{X}$	4.15	5.48	4.08	5.23
	s	2.03	3.78	1.81	2.18
line return sweep in degrees	$\bar{X}$	28.07	25.60	23.08	20.11
	s	1.79	1.69	2.27	1.46
total reading time in sec	$\bar{X}$	12.58	12.27	12.49	12.39
	s	1.66	2.68	2.56	2.28

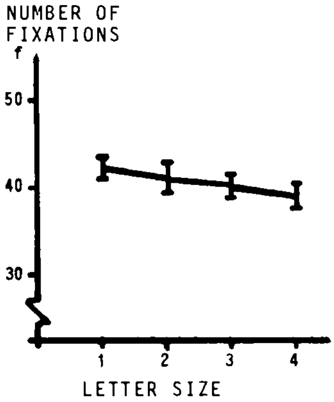


Figure 5
Number of fixation as a function of letter size,
1 = large letter size,
4 = small letter size

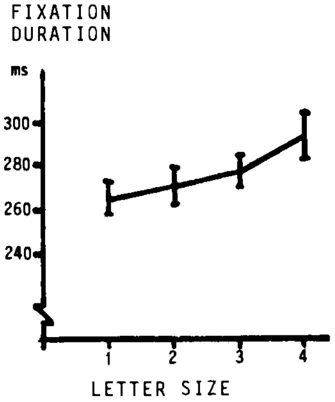


Figure 6
Fixation duration as a function of letter size,
1 = large letter size,
4 = small letter size

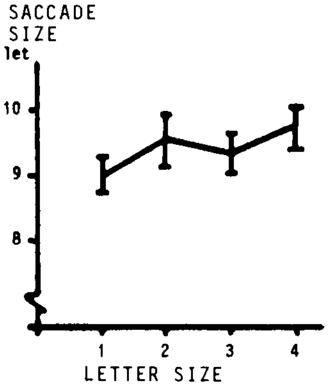


Figure 7
Progression size measured in letter positions as a fonction of letter size,
1 = large letters
4 = small letters

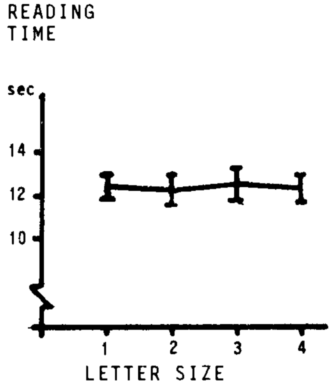


Figure 8
Total reading time as a function of letter size,
1 = large letters,
4 = small letters

When comparing the eye movement parameters of this experiment with those of the first one, one notices that the number of fixations for letter distance 2 compared to letter size 1 were 50.44 versus 42.31 respectively, in spite of the fact that letter size and spacing in the two texts were identical. This discrepancy could have arisen by the fact that the corrective saccades placed at the beginning of a line in the second experiment were excluded in the calculation of the data. All other parameters are in agreement: variation of letter distance or of letter size did not influence in any way the total reading time, however, only the eye movement parameter. Thus, in skilled adult readers, letter distance was much more influential than letter size upon eye movement parameters - a finding which corroborates the data previously established with children (Heller & Heinisch 1985).

Although the range of letter size variation was nearly the same as in the experiments reported by Tinker 1963 (except the 14 point size) we could not reproduce his results concerning fixation frequency, reading time and regression frequency. This may possibly be due to the different ways of changing the letter sizes, hence to the uncontrolled variable letter spacing in the experiment of Tinker & Paterson (1955).

The data found, however, fit O'Regan's "grain model", i.e. there is no significant effect of letter size on progression size (measured in letter positions), hence the effect of varying viewing distance is comparable of that of photographical size reduction of letters (in the given range of variation). According to the results in the reading experiment of O'Regan (1981) a linear regression on the saccade size data (no significant differences) would indicate a small positive slope, i.e. a decreasing letter size leads to an increasing progression size measured in letter positions. Concordant with the study of O'Regan, Levy-Schoen & Jacobs (1983) a slight increase of fixation duration ($p < .01$) in smaller letters can be stated. But because there is no effect on saccade size this cannot be interpreted in the usual way of the visual span model (McConkie & Rainer 1975). Obviously the visual span is not a "window" with a more or less fixed visual angle, but it depends on the processing effort that must be expended at the given fixation location. It seems reasonable to assume according to O'Regan, Levy-Schoen & Jacobs that the longer lasting fixations with smaller letters are due to greater effort in identifying the distinctive features of the letters.

Finally it can be stated that the studies have demonstrated that our experimental setup is rather useful in indicating even small typographical variations. Although total reading time did not vary, different eye movement patterns can be shown depending on letter spacings and letter sizes and the results are replicable.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

READING WITH AND WITHOUT EYE MOVEMENTS

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The rapid serial visual presentation (RSVP) method allows for simulation of some of the properties of normal eye fixations; for example, text can be displayed in successive units for 250 msec durations to a common location on a computer-controlled screen. Text presented in this way can be read relatively normally, but without the need for eye movements. Research has shown that optimal RSVP conditions include successive units that average about two to three words in length and reflect some level of syntactic structure. These conditions result in levels of comprehension that, at least for some readers, are superior to those obtained from reading pages of text with normal eye movements.

INTRODUCTION

Much of what is known about the process of reading necessarily has been inferred from its effects upon the reader. That is, most theories of reading are based upon a combination of what the reader stores about the text being read and what can be retrieved during a later test of comprehension and memory. Very few methodologies exist for measuring ongoing processes of reading without at the same time interfering with normal reading behavior. One such method consists of unobtrusively monitoring a reader's eye movement patterns. Not only are eye fixations and saccadic movements the major overt realizations of reading processes, but they also indicate which aspects of the text are sampled by the reader and for how long they are processed. We know, for example, that the skilled reader makes about four fixation pauses per second, and, ignoring regressive saccades, that these move ahead by an average of about eight to ten character spaces. In this way, about two-thirds of the words are actually fixated, some of them several times. We also know that some aspects of the text viewed peripherally are used in determining saccadic extent, since function words tend to be passed over more than content words, and fixations tend to be located near the left-center parts of words rather than at the ends (Just & Carpenter, 1980; Rayner, 1979; O'Regan, 1981).

McConkie (1983) has pointed out that despite the knowledge gained from studies of eye movements, there are a number of difficulties inherent in basing theories of reading on eye movement and fixation data. These include the facts that more than one word can be seen well enough to be processed on each fixation, fixation duration is not a direct reflection of processes depending on information abstracted from that fixation, and both fixation duration and saccadic extent are determined by processes that are largely unknown.

As a new approach to the study of reading behavior, we have been investigating the ability of people to read without eye movements, with text presented successively in small units to a single location on a CRT screen. This research has several purposes: (1) to develop and test theories of reading behavior in the unique situation of having relatively complete control of the text input side of reading, (2) to determine the optimal means of presenting text on a CRT screen in a search for methods that might be improvements over standard pages, and (3) to determine whether any of the new text presentation methods might have useful applications in reading instruction for beginning or remedial readers.

Reading Computer-Displayed Text

An increasing percentage of what is read at home, at work, and in school environments will be presented on CRTs or other electronic display devices. For this reason alone it is important to determine how text should be displayed to promote rapid reading for comprehension. A common method is to present paragraphs of 200 to 300 words as single "pages" that fill the display screen and can be read with normal eye movements. Electronic pages can generally be read about as well as printed pages, although at equivalent levels of comprehension they are read a bit more slowly (Kruk & Muter, 1984; Muter, Latrémouille, Treurniet, & Beam, 1982).

Displays under computer control offer a number of other possibilities, however, and some of these might prove to be superior to pages for some readers and task environments. For example, text can be moved more or less continuously up from the bottom of the screen by lines ("scrolling") or from the right to left along a single line ("leading"). Both scrolling (Kolers, Duchnicky, & Ferguson, 1981; Oléron & Tardieu, 1978) and leading (Granaas, McKay, Laham, Hurt, & Juola, 1984; Sekey & Tietz, 1982) have been shown to be generally inferior to standard pages. This result is not surprising in that while reading moving text, normal eye movement patterns must be replaced with those requiring additional anticipations and compensations for the movement of the text itself.

A more promising method of presenting text on a computer screen is one that eliminates the need for eye movements altogether. This can be done by using RSVP, or rapid serial visual presentation, in which successive text segments of one or more words are presented to a common location on the display (e.g., Bouma & deVoogd, 1974; Forster, 1970; Gilbert, 1959; Raygor, 1974). In this way, it is possible to simulate the results of successive eye fixations in normal reading by showing a new, short segment of text every 250 msec or so. Most studies of RSVP reading have used display conditions that approximate eye fixations and have found that RSVP reading perfomance is usually no worse, and sometimes better, than that obtained for normal pages (Bouma & deVoogd, 1974; Juola, Ward, & McNamara, 1982; Potter, Kroll, & Harris, 1980; Raygor, 1974; Ward & Juola, 1982).

At first it appears counterintuitive that the elimination of normal eye movements could in any way be conducive to reading efficiency. It has been argued that normal deviations from an invariant scanning pattern reflect changes in processing load or decisions about how to sample information from text (e.g., Just & Carpenter, 1980; Lévy-Schoen & O'Regan, 1979; McConkie, 1979). Thus, variations in saccadic extent and fixation duration are thought to be necessary concomitants of normal reading processes, much as are regressive eye movements and pauses, none of which are present in the methodical RSVP format. Because most previous research is consistent in showing that reading comprehension is no worse for RSVP displays than for normal pages, any cost due to the invariance of display parameters in RSVP must somehow be compensated by benefits due to the elimination of normal eye movements.

It is possible that typical eye movements are inefficient because normal readers tend to be conservative, moving their eyes forward in smaller saccades and in more frequent regressive movements than are necessary for clear resolution of the text (Crowder, 1982; Hochberg, 1976). Eye movements themselves sometimes result in inaccurate fixation locations, particularly in return sweeps to new lines of text, necessitating corrective saccades (McConkie, 1983). Another inefficiency and potential problem for normal reading lies in the fact that although the eye guidance system subjectively appears to be automatic, some cognitive processing capacity unavoidably must be devoted to the control of eye movements and the determination of fixation duration. This demand for cognitive resources could diminish the capacity available for other processes such as the main task of comprehension. Thus, at least the potential exists for discovering new methods of text presentation that eliminate the need for eye movements and also improve the efficiency of reading for comprehension.

Optimizing RSVP Reading

Given that most studies have shown a near equivalence between page and RSVP formats, it is of interest to determine whether an optimal RSVP method can be found that might result in improved reading performance relative to pages. In a series of experiments, we have sought to use eye movement data and theories of reading behavior to guide our selection of the parameters of RSVP displays. These parameters include (1) the number of characters or words shown at one time (window size), (2) the amount of overlapping text between successive windows, (3) the amount of time that each successive text segment is shown (window duration), and (4) the degree and type of text structure included in the text segments. In most of our research, each window contains whole words only, so window size has been entered as a parameter in a text parsing program that selects successive segments from a text file that are as close as possible to the desired length (in character spaces) while not truncating any words.

We know that the field of useful vision in normal reading extends about 20 characters horizontally around the point of fixation, and most of this field extends to the right of the actual fixation point. However, only the leftmost, or foveal, part of this region is seen clearly enough to identify words (e.g., McConkie & Rayner, 1975). The rightmost part of the field could be used for pre-analyzing words that will appear closer to the fovea in the following fixation or for guiding the saccadic movement to an appropriate place for that fixation (McConkie 1979; Rayner, 1978). Most previous RSVP research (e.g., Forster, 1970; Masson, 1983; Potter et al., 1980) has used successive windows of single words. This procedure has the dual limitation of possibly under-utilizing the perceptual information-processing capacity of the visual system and also of requiring a rapid succession of displays in order to achieve normal reading speeds (i.e., one word every 200 msec equals 300 words per minute, WPM).

In an experiment designed to determine the optimal window size for RSVP displays (Cocklin, Ward, Chen, & Juola, 1984, Exp. II), the mean number of characters per window was varied from five to twenty and mean window duration from 76 msec to 992 msec to produce imposed reading rates from 200 to 800 WPM. In almost all conditions, comprehension performance was superior for intermediate window sizes, reflected in a significant quadratic trend relating comprehension level to window size which peaked between 12 and 13 characters. This trend did not interact with text difficulty or presentation rate. The peak performance for windows of about two to three words in length is an interesting corroboration of estimates of the functional visual field based on eye movement data, and it also points to the self-imposed limitations of previous RSVP research using one-word windows.

Other design parameters chosen to simulate the visual experience of normal reading have been less successful in improving RSVP reading. For example, the inclusion of overlapping text segments on successive windows in RSVP, to mimic the successive parafoveal and foveal views of text elements that occur in normal reading, resulted in lower comprehension levels than windows with no overlaps presented at the same overall rate (Cocklin et al., 1984, Exp. I). In another study, varying window duration in order to correspond to the expected processing time per word derived from Just & Carpenter´s (1980) regression model produced no advantage over a constant window-duration condition (Ward & Juola, 1982). These results suggest that optimal RSVP conditions do not necessarily need to mimic eye movement data, and that, in fact, executing a series of eye fixations and saccades might not be the best way to read a text.

Besides examining the effects of window size, successive overlaps, and variations in window duration on the readability of RSVP text, we have tested the effects of window structure. It is possible that Cocklin et al.´s (1984) finding of an advantage for windows of 12 to 13 character spaces was purely a perceptual effect. That is, the advantage for windows of intermediate size could be due to optimum loading of a visual short-term buffer that functions in relatively low-level processes such as lexical access. Smaller windows could underutilize perceptual resources, whereas large windows would result in loss of information due to capacity limits. On the other hand, windows of intermediate size could also facilitate higher-level cognitive and linguistic processes concerned with text parsing and integration of units from a visual buffer into a meaningful macro representation. In the latter case, reading RSVP displays could be improved if successive windows were specifically chosen to reflect local units of linguistic organization, rather than being randomly-selected segments from the text that average 12 to 13 character spaces.

In a third experiment reported in Cocklin et al. (1984), we contrasted comprehension scores for RSVP windows chosen to be as close as possible to a constant size of 13 characters with those selected to contain short "idea units" that also averaged 13 character spaces in length. Idea units were defined as the consensus among four independent judges who divided the paragraphs into short groups of words (totalling 20 or fewer characters) that belonged together to express a single idea. The results showed a clear advantage for idea-unit segmentation. (It should be noted that idea units were selected by consensus in the Cocklin et al. study, but in the research presented here, text parsing into idea units was performed by a computer program. This program was written by Michael Granaas (1985) and revised by Michael Liebhaber for the present research. It uses punctuation, a list of critical function words, and an upper limit on segment length to produce segments that have about a 90 percent agreement with idea units selected by human judges.)

Based on research using a wide range of text difficulties and presentation rates, we have concluded that the optimal RSVP conditions are those that include windows averaging about 12 to 13 characters in length, selected, when possible, to include short phrases or idea units as defined here. Presentation rate can be controlled by manipulating window duration, with 250 msec durations producing a reading rate of about 600 WPM. Comprehension is also improved if a 250 to 500 msec blank window is inserted between sentences (Masson, 1983), presumably to enable sentence wrap-up and integration processes to occur (see also Just & Carpenter, 1980). We shall next consider an empirical comparison of this optimum RSVP condition with electronic pages in a study of reading comprehension.

READING PAGES VS. RSVP DISPLAYS: AN EMPIRICAL STUDY

In a recent review of RSVP research, Potter (1983) remarked that the method has not been tested adequately with practiced subjects or with readers younger and less-skilled than college students. There apparently has been only a single study of the effects of individual differences in readers´ skill levels on the readability of RSVP vs. page formats (Chen, 1982). Chen presented short paragraphs either as whole pages on a CRT screen or as RSVP sequences. The windows averaged 12 character spaces in length, but they were not linguistically parsed. The texts were visible for the same total reading time in RSVP and page conditions, and comprehension and memory were assessed by a sentence recognition task. The subjects were college students who were divided into high-skill and low-skill groups. There were no significant differences in performance between the RSVP and page conditions for the high-skill group. For the low-skill group, however, there was a significant advantage in retention of text meaning for the RSVP displays. This result indicates that RSVP might be particularly useful for improving the reading skills of less-able readers and for applications to instruction of beginners and remedial readers. A test of the effects of extended practice with RSVP reading for good and poor readers was the main purpose of the research reported here.

Method

The subjects were 19 students from a middle school in Lawrence, Kansas, who ranged in age from 12 to 15 years. About half of the students were selected specifically from remedial reading classes in their school. Each student was run individually for five one-hour sessions on separate days. On the first day, each student was given a reading test, which consisted of 10 paragraphs from the McCall-Crabbs Standard Test Lessons in Reading, each followed by about 10 comprehension questions. The test was designed to measure each student´s reading rate and comprehension level when reading at his or her own pace from a printed page. The first day ended with the presentation of 10 similar paragraphs using the RSVP format. These were presented on a Televideo display terminal controlled by a Sage II minicomputer. The texts were parsed into idea units averaging about 13 character spaces in length. Each window was shown for about 500 msec, with a blank 500 msec between sentences, to produce a presentation rate of about 200 WPM. Although this duration permits eye movements within a window, informal observations and subjective reports bear out the claim that the most typical strategy used in RSVP reading is to select a convenient viewing position and to attempt to maintain it throughout a paragraph.

On the second day, all subjects read 10 paragraphs in the RSVP mode and 10 paragraphs in the page format, along with four practice paragraphs in each format. Paragraphs in the page condition were shown for the same total amount of time as they were in the RSVP condition. On days three and four, subjects read four practice paragraphs and 20 experimental paragraphs in the RSVP method only. The fifth day was the same as the second; data were collected for 10 paragraphs in both page and RSVP conditions. All paragraphs were followed immediately by four four-alternative multiple-choice questions.

Results

The overall results for RSVP and page conditions are shown in Figure 1. Mean percent correct responses to the comprehension questions is plotted against the five daily sessions for RSVP and page conditions separately.

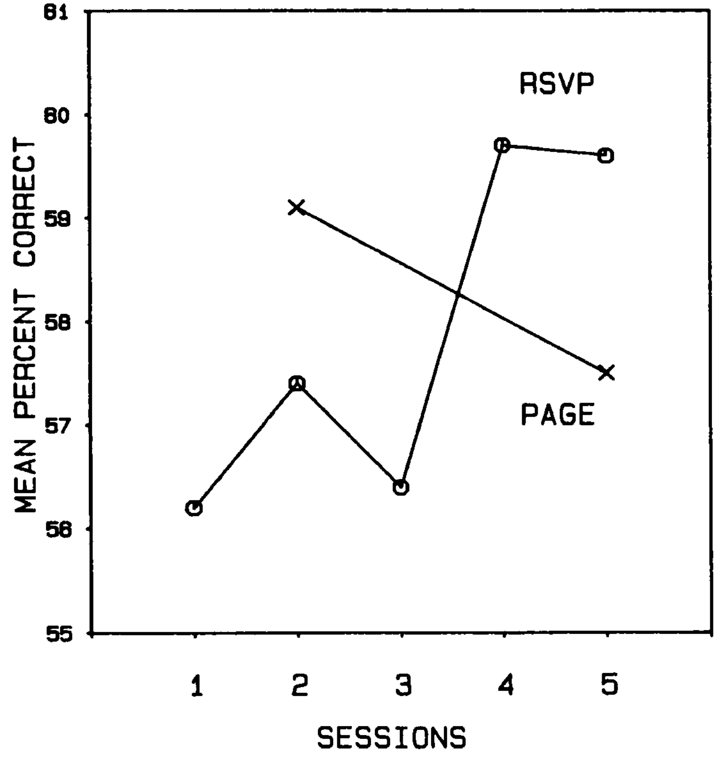

Figure 1
Mean Percent Correct Responses to Comprehension Questions
Plotted Across Daily Sessions for RSVP and Page Conditions

Data were collected on all sessions for RSVP paragraphs, but data for the page format were obtained on Sessions 2 and 5 only. As can be seen in the plot, performance improves steadily over days of practice for RSVP reading, being below the level of page peformance on Session 2 and above that for pages on Session 5.

In a second analysis, the subjects were divided into a group of "good readers" and a group of "poor readers" based on the results of a standardized reading test given in their school. The 10 good readers scored above the 73rd percentile on national norms (mean = 87) and the nine poor readers scored below the 57th percentile (mean = 40). The standardized test scores correlated with our own measures of the subjects' reading abilities taken on Session 1. The good readers read the 10 printed paragraphs at an average rate of 180 WPM with a mean comprehension score of 74 percent. For the poor readers, these data were 154 WPM and 60 percent, respectively. Figure 2 presents the data for Sessions 2 and 5 for good and poor readers separately. There is a non-significant advantage for the page format for good readers, whereas the poor readers initially show no comprehension differences between formats. By Session 5, however, practice in reading RSVP displays leads to an advantage over the page method of text presentation for the poorer readers.

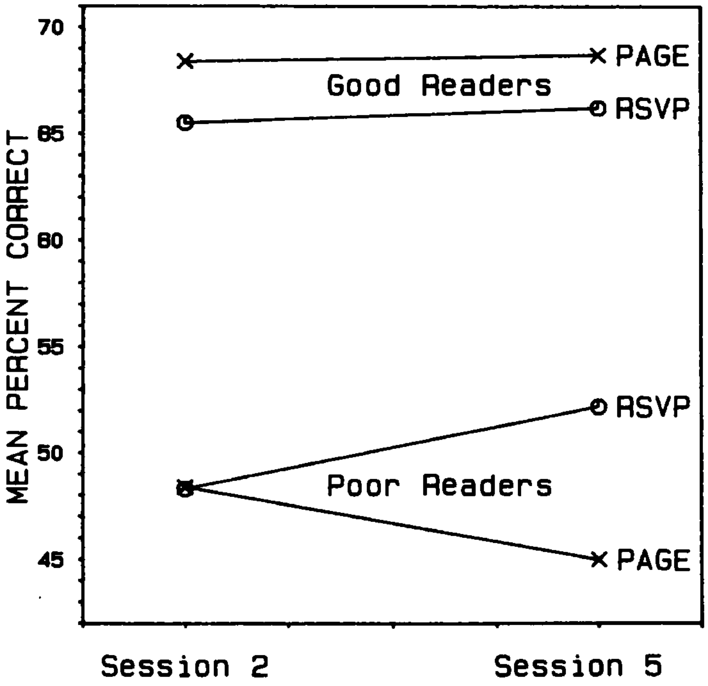

Figure 2
Mean Percent Correct Responses to Comprehension Questions
on Sessions 2 and 5 Plotted for Good and Poor Readers
in RSVP and Page Conditions

SUMMARY AND CONCLUSIONS

The present results closely replicate those of Chen (1982). He found that good college student readers understood and remembered information in text about as well when confronted with either the RSVP or page format. Poorer college student readers performed better for texts presented in the RSVP mode. In the present study, teenage readers who were above average in their reading skills showed no significant advantage for pages over RSVP. However, less skilled readers were able, with practice, to achieve a seven percent comprehension advantage for texts presented via RSVP. Most studies of RSVP vs. page reading have found no comprehension differences between the two formats. Studies of individual differences, however, have demonstrated that reading ability can be improved by the use of RSVP displays, at least for less-skilled readers. It is possible that the RSVP method helps poorer readers by replacing their relatively inefficient eye movement patterns with an imposed, regular sequence through the text. It is also possible that dividing a text into small idea units in the RSVP format assists with text parsing, comprehension, and integration processes (e.g., Martinez, Ghatala, & Bell, 1980; O'Shea & Sindelar, 1983). Although an adequate explanation of the advantage for RSVP over normal pages awaits further research, it is clear that the RSVP method can improve the reading abilities of some subgroups of the population. This advantage for RSVP could readily be implemented in computer-assisted instruction programs for beginning readers and those in need of remediation. The positive results found for poorer readers in Chen's (1982) research and in the present study strongly suggest that poorer readers could be taught to learn to read better and faster through elimination of the demands placed on them by a static text that must be scanned by eye movements.

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EYE MOVEMENTS: From Physiology to Cognition
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THE COMPONENTS OF READING TIME: EYE MOVEMENT PATTERNS OF GOOD AND POOR READERS

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This paper discusses the results of a study which compared groups of IQ-matched readers varying in reading skill. The subjects read pairs of sentences containing either pronominal or noun phrase anaphor. The physical distance between anaphor and antecedent was varied. The results show a complex pattern of interactions which can be summarised in terms of different global strategies adopted by good and poor readers. A significant aspect of the data is the presence of trade-offs between fixation duration and number of forward fixations and between different types of reinspection. Measured reading time does not reveal these differences, but the failure cannot be related to lack of statistical power. It arises because different patterns of eye movement may be executed in the same total time.

INTRODUCTION

In this paper we examine, by means of an analysis of the eye movements of good and poor readers, some of the components of Reading Time. This ubiquitous measure is routinely used in much cognitive and psycholinguistic research as an index of comprehension (Haviland and Clark, 1974; Sanford, Garrod and Bell, 1979); anaphor resolution (Garnham, 1984; Garrod and Sanford, 1977); inference making (Vonk, 1984); and problem solving (Kennedy, 1983). Reading Time (RdT) is the total time taken by a subject to read a sentence (or line of text) in a self-paced presentation. Its use reflects the assumption that there is an orderly relationship between the complexity of materials and the total time taken to read them. It is, however, a somewhat crude measure. Furthermore, it is not obvious that the time to read (in the sense of inspect) the words of a text is the same as the time to read (in the sense of comprehend). This problem was noted by Haviland and Clark (1974) in an influential early paper, but cannot be satisfactorily solved.

A measure of RdT for a single line of text can be decomposed into the pattern of eye movements and fixations which underlie it. For this reason it is often argued that eye movements represent a more sensitive measure of processing load (e.g. Rayner, Carlson and Frazier, 1983). However, this claim is normally taken to relate to statistical sensitivity. That is, the fundamental assumption is made that RdT, although somewhat 'noisy', is capable *in principle* of detecting moment-to-moment variations in processing load. Problems posed by use of the RdT measure are taken to be ones which can be dealt with by the proper adjustment of statistical power. We wish to argue here that the use of RdT brings problems which are quite unrelated to questions of sensitivity and statistical power. To make this point it is necessary to consider both RdT and eye movement measures over the same sample of experimental materials.

A single observation of RdT comprises a number of discrete components:

$$RdT = nFf + jFr + kB + (n+j-1)S + K$$

where n and j refer to the numbers of forward and regressive fixations (of duration Ff and Fr) and k to the number of blinks (of duration B). To this total fixation time must be added the duration of related saccades (S) and a constant duration (K) representing recorded eye movement data which the clustering algorithm cannot reliably allocate to any particular fixation. The assumption underlying the use of RdT is that no significant differences are to be found among the functional relationships holding between each component and the experimental manipulation under consideration, or that a particular component varies randomly. We believe that this is questionable for three reasons.

(1) There are principled grounds for distinguishing first- and second-pass eye movements. These refer to the fixations and associated saccades which occur on the first encounter with the words of a given text and to all subsequent reinspections. The sources of control over these two classes of fixation differ (Frazier and Rayner, 1982; Kennedy and Murray, 1984). First-pass fixations are primarily influenced by low-level properties of the text and by the physical length of words (O'Regan, 1980). Second-pass fixations index the reader's attempts to find coherence in the text. Thus, second-pass fixations may relate to syntactic ambiguity and to various forms of cross reference within and between sentences (Kennedy, 1978; Carpenter and Just, 1977).

(2) The reader may deal with local processing demands by extending the current fixation duration or by making more fixations (or both). These 'strategies' may relate in different ways to task demands (Kliegl, 1982).

(3) Readers of differing ability vary in the pattern of eye movements they make. Furthermore, there are systematic dependencies between different classes of eye movement measure (Olson, Kliegl and Davidson, 1983). Thus, for example, in a group of disabled readers, subjects who make longer saccades make relatively more regressive fixations.

These complex dependencies have important implications for the interpretation of measured RdT, since the possibility arises that subjects may modulate patterns of inspection (trading off one component against another) in ways which are *in principle* undetectable in the more global measure.

In the experiment described here we examined the factors (1) to (3) by means of the following manipulations. First, we made use of materials containing anaphor and hence likely to induce reinspections (Kennedy, 1978). This allowed for separate analyses of first- and second-pass eye movements. Second, the demands imposed by the materials were manipulated by varying both the physical location of the antecedents of anaphoric expressions and the syntactic complexity of the sentences. Third, we employed readers of differing ability.

METHOD

Materials

Sets of Sentence-Question pairs were constructed of the following form:

(1) The man shot the tiger in the jungle. Was he hunting?
(2) The man shot the tiger in the jungle. Was the man hunting?
(3) In the jungle the man shot the tiger. Was he hunting?
(4) In the jungle the man shot the tiger. Was the man hunting?

In (1) and (2) there is an identical initial sentence followed by a question containing either a noun phrase or pronominal anaphor. Since the antecedent of the anaphor occurs near the beginning of the sentence, these are referred to as Early Antecedent sequences. In (3) and (4) the same contrast is found in the questions between noun phrase and pronominal anaphor but the antecedent is physically closer. This manipulation makes sequences (3) and (4) somewhat more difficult than (1) and (2). The preposed adverbial structure itself is more complex, and the potential ambiguity of reference in the anaphor is accentuated, since the preferred strategy of assigning the antecedent to the first-mentioned noun phrase fails. Thus, although the antecedent is physically closer, the sentences are slightly harder to process and the questions more difficult to answer.

There were 32 sets of Sentence-Question pairs. From these, four counterbalanced item groups were derived. Each subject received an equal number of items from the four conditions, but saw only one version from each set. In addition, there were 10 practice sequences.

Subjects

These were 32 schoolchildren aged between 10 and 11 years from three local primary schools. Two matched groups of 16, designated 'Good' and 'Poor' readers, were chosen on the basis of a standard reading test (NFER Reading Test BD). These groups differed markedly in reading performance, while being closely matched for IQ on a standard scale of non-verbal intelligence (Raven's Matrices). Scores for the two groups on these pre-test measures are shown in Table 1.

Table 1

	Reading Score		I.Q.	
	Mean	SD.	Mean	SD.
Good Readers	117.6	3.4	116.8	5.4
Poor Readers	99.3	3.5	120.4	6.1

The two groups did not differ significantly in I.Q. ($t(30) = 1.78$). There is, in fact, a small difference in favour of the Poor group. The difference in Reading score between the two groups was highly significant ($t(30) = 14.85$, $p < .001$).

Procedure

(a) Display. The experimental materials were presented on a computer-driven display under subject control. Each trial began with the appearance of a warning marker at the left margin of the display screen. The subject's first button-press was followed by display of the first sentence. When this had been read, a second button-press displayed the question to the right of the sentence. Sentence and Question occupied a single horizontal line on the display and both remained on view until subjects responded to the question by pressing an appropriate "yes" or "no" button. Subjects were asked to read at their own pace and to answer the questions as fast and accurately as possible. A calibration display, used by the eye movement recording system. occurred every three trials. In this, subjects fixated in turn a sequence of five letters located across the display screen.

(b) Eye Movement Recording. Horizontal eye movements were recorded using a standard infra-red limbus-tracking device mounted on spectacles. Head movement was restricted by the use of a dental composition bite bar. Output from the eye movement detector was sampled every 10 msec and stored on a computer for later analysis.

RESULTS AND DISCUSSION

Reading Time

Mean RdT for Early and Late Antecedent sentences is shown in Figure 1. As is apparent from the figure, Good readers were faster than Poor, although the data are highly variable and the difference is only marginally significant (F1 (1,24) = 3.37, p = .075; F2 (1,28) = 83.50, $p < .001$). There is a tendency for Late Antecedent sentences (which are more complex) to be read more slowly than Early Antecedent. However this effect is only reliable for Good Readers (F1 (1,12) = 5.04, $p < .05$; F2 = 5.49, $p < .05$).

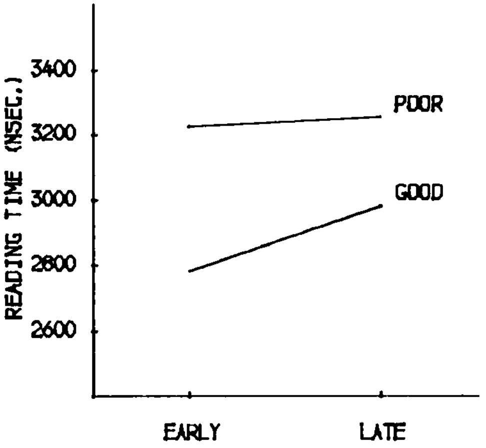

Figure 1. Mean Reading Time for Early and Late Antecedent Sentences

Mean RdT for the questions is shown in Figure 2. In this case, the results are given in terms of both Type of Anaphor and Position of Antecedent. For compatibility with later eye movement analyses, these data include both correct and incorrect responses. (Analyses of data for correct responses only, show an almost identical pattern and do not lead to any modification in our later arguments).

The results again reveal Good readers to be considerably faster than Poor (F1 (1,24) = 13.10, $p < .002$; F2 (1,28) = 97.61, $p < .001$). The absolute difference in RdT between the sentence and question is of no consequence, since the questions are, in general, much shorter. Both Good and Poor readers take longer to read questions containing noun phrase anaphors than those containing pronouns. This result should be interpreted with care. Questions containing the noun phrase anaphor are one word longer on average and the difference is approximately the duration of one fixation. However, there is a tendency for this Noun-Pronoun difference to be greater following Early Antecedent sentences. The interaction is significant (F1 (1,24) = 4.46, $p < .05$; F2 (1,28) = 4.55, $p < .05$) and seems to reflect the particular difficulty associated with pronominal reference to Late Antecedent sentences, where the appropriate referent is more ambiguous. This problem does not arise with noun phrase anaphors which obviously specify the particular antecedent. It is important to note, however, that none of these trends differ between groups. All interactions with Type of Reader are non-significant (all F1 and F2 < 1).

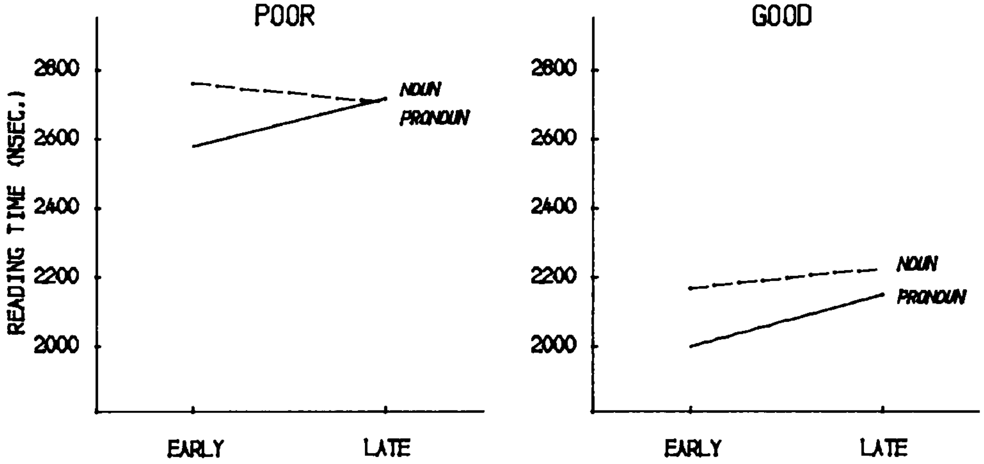

Figure 2. Mean Reading Time in Questions following Early and Late Antecedent sentences. The data show Questions containing Noun Phrase and Pronominal Anaphor separately

It is possible now to summarise the conclusions which arise from an analysis of RdT alone. The dominant factor which differentiates the performance of Good and Poor readers is absolute speed: Good readers are faster. There is a suggestion in Figure 1 that Good readers read Late Antecedent sentences more slowly than Early Antecedent sentences, while this difference is unclear in the case of Poor readers. However, there is no evidence at all to suggest that the two groups differ in the way they deal with the various linguistic and physical manipulations in the questions. If RdT can be taken to index processing load, the most we may conclude is that both groups have difficulty dealing with pronominal reference to Late Antecedent sentences.

We turn now to what is effectively a reanalysis of these RdT data in terms of their component elements: the number and duration of fixations and reinspections across Sentence and Question as they are read.

Fixation Duration and Number of Fixations

The average duration of fixations and the number of fixations made during the reading of Sentence and Question are shown in Figure 3. Considering first the results obtained as subjects read the initial sentence, it is clear that Good and Poor readers deal with the difficulty inherent in Late Antecedent items in different ways. The weak interaction present in Figure 1 relates to the fact that the Good group modulate RdT primarily by an increase in the number of fixations made (F1 (1,12) = 6.59, p <.02; F2 (1,28) = 5.60, p < .02) and show no change in the average duration of fixations (F1 and F2 < 1); whereas the Poor group show no change in the number of fixations made for the two sentence types (F1 and F2 < 1), but exhibit a tendency to fixate longer in Late Antecedent sentences (F1 (1,12) = 3.59, p = .08; F2 (1,28) = 3.69, p = .06). It is clear from this analysis why such differences in reading style are so poorly indexed by measured RdT. Total time to read may be roughly derived from the function:

RdT = No. of Fixations x Average Duration

but since these two components bear different functional relationships to sentence type in the two groups, the trends are - from the perspective of RdT - obscure.

A very similar methodological interpretation may be placed on the results for Questions. Here, of course, we must distinguish both Type of Antecedent and Type of Anaphor. Overall, in contrast to the manner in which the initial sentence is processed, Poor readers make more fixations than Good when dealing with the Questions (F1 (1,12) = 4.95, $p < .03$; F2 (1,28) = 22.22, $p < .01$). There is little reliable variation in the pattern of fixations within the two groups, other than that due to the extra word in noun-phrase anaphors.

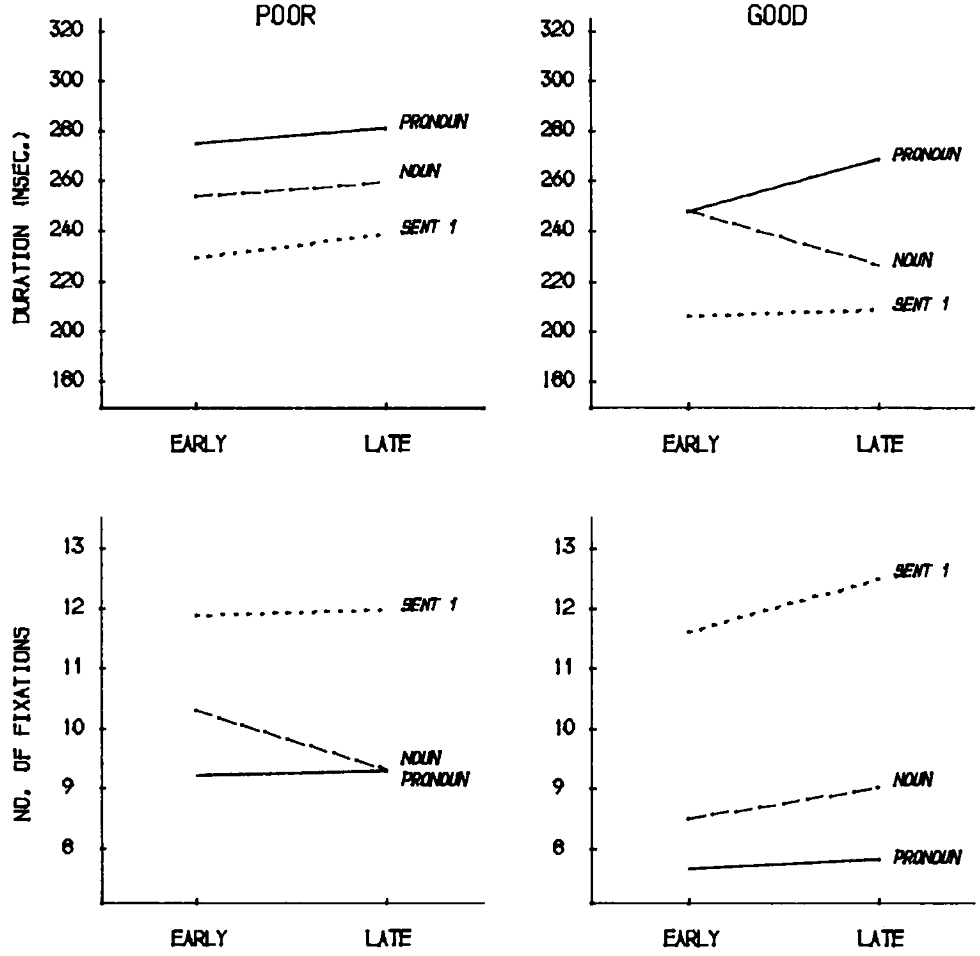

Figure 3. Fixation Duration and Number of Fixations in Sentences and Questions

The apparent interaction in the lower left panel of Figure 3 between Type of Antecedent and Type of Anaphor for the Poor group is far from significant (F1 (1,12) = 1.36; F 2 (1,28) = 1.53). For the Good group the modulation in RdT apparent in Figure 2 arises largely from systematic changes in fixation duration. In this case, of course, Noun-Pronoun differences are not artifactual. The interaction evident in the top right panel of Figure 3 is highly significant (F1 (1,12) = 11.29, $p < .01$; F2 (1,28) = 11.55, $p < .01$). The Poor group show an increase in fixation duration in questions containing pronominal anaphors (F1 (1,12) = 7.09, $p < .02$; F2 (1,28) = 10.42, $p < .01$) but there is no hint of an interaction (F1 and F2 < 1).

Blink Duration

Comparing Figures 2 and 3, and bearing in mind that RdT should relate roughly to the product of the number of fixations and their duration, it is pertinent to ask where the interaction between Type of Antecedent and Type of Anaphor apparent in Figure 2 arises. For Good readers this interaction appears largely to result from the modulation of fixation duration. This is not true for Poor readers. The variation they show in number of fixations does not adequately account for it. The answer appears to lie in systematic variation in the distribution of blinks. Since blinks in eye movement measurement are normally treated as gaps in the record, there have been few attempts to date to relate their frequency or duration to text variables. This is unfortunate, since our data suggest that their occurrence is non-random.

Figure 4 shows the mean cumulated total duration of blinks per sentence for the various subconditions. No reliable differences were observed during the reading of the sentence, whereas the pattern of results for Questions differs markedly in the two groups. The absolute difference in Blink Duration to noun phrase and pronominal anaphors differs for Good and Poor readers. The interaction with type of reader is significant (F1 (1,24) = 7.11, $p < .02$; F2 (1,28) = 5.43, $p < .03$). The interpretation of this is fairly straightforward. Good readers show no significant modulation in Blink Duration between conditions. Poor readers, in contrast, show greater Blink Duration in noun phrase anaphors (F1 (1,12) = 7.52, $p < .02$; F2 (1,28) = 5.78, $p < .02$), and the interaction between Position of

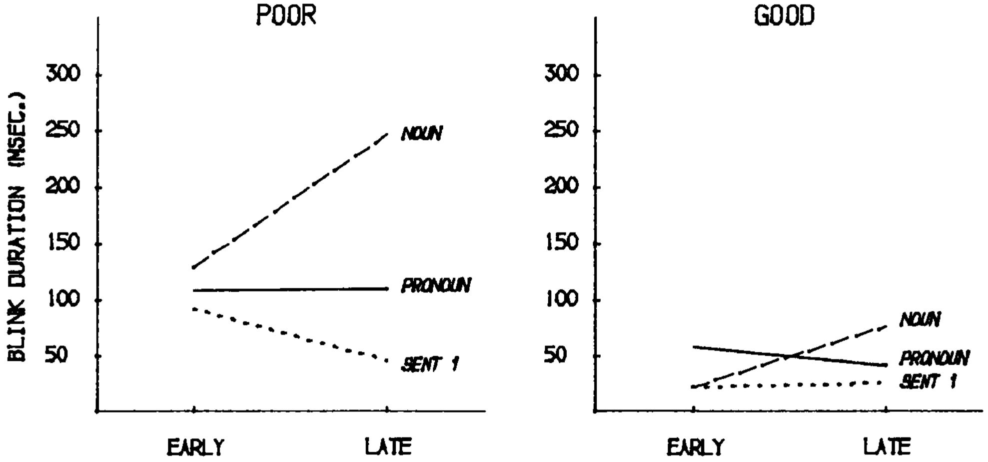

Figure 4. Mean Cumulated Total Duration of Blinks per Sentence

Antecedent and Type of Anaphor is also marginally significant; (F1 (1,12) = 4.29, $p < .06$; F2 (1,28) = 4.14, $p < .05$). That is, there is some tendency for the noun-pronoun difference to be greater following Late Antecedent sentences.

It is tempting to conclude from this that Blink Duration may only be of relevance in the interpretation of eye movement records involving problem solving, but obviously more data are needed to settle this question. Our results clearly indicate that for Poor readers an important component in measured RdT is time spent blinking. When these data are considered together with the number and duration of fixations, it is possible to account for the obtained variation in RdT. However, the crucial point is that these three components taken independently, relate to text manipulations in *different* ways, and do so differently for Good and Poor readers. Thus, there are circumstances in which RdT is incapable of detecting significant variations in the way readers process text.

Reading Style

Having secured this methodological argument, we may now explore in more detail the apparent differences in reading style which characterise Good and Poor readers and offer some theoretical interpretation of the overall pattern of results.

In the case of the initial sentence, the results may be roughly summed up as showing Good readers to look *more* and Poor readers to look *longer*. The reading test scores which differentiate the two groups obviously suggests that, as a general strategy, it is the Good reader's style which is more effective. Yet in the case of the Questions, more or less the opposite pattern of results obtains: Good readers vary the duration of their fixations, Poor readers make more fixations. Superimposed on these trends we find a striking variation in Blink Duration - part of the way Poor readers deal with Questions involves an increase in the time spent blinking; no such effect obtains for the Good group.

We wish to account for this constellation of findings as follows. Good readers carry out a more comprehensive analysis of the initial sentence than do Poor readers. This is hinted at in the RdT measure and shown quite clearly to relate to an increase in the number of fixations made. Following the argument presented in the Introduction, we hypothesize that this increase is primarily in second-pass inspections (regressive fixations) which relate to the reader's efforts to achieve a coherent representation of meaning. Thus when a Question is presented, for the Good reader much of the necessary mental work has already been completed. Most of the additional processing required for the more difficult questions is reflected in the modulation of fixation duration. This is not true of the Poor reader, for whom the Question poses a greater challenge. It is open to readers in this group to deal with Questions by launching selective reinspections, but this strategy is, it appears, less available to the poorer reader. As a consequence, we find an increase in 'time out' - indexed by blinks - and overall changes in fixation duration.

Clearly to establish the validity of this line of argument we need to examine the manner in which regressive eye movements are deployed in the two groups. As a first step consider, as a subset of the total number of fixations, fixations following a right-to-left saccade. These comprise the majority of second-pass fixations.

Regressive Fixations

Figure 5 shows the number of regressive fixations in the initial sentence and during responses to questions, plotted as a proportion of the total number of fixations made. This procedure removes artifacts due to varying baselines and the measure is similar to the Regressive Fixation Index derived by Olson, Kliegl and Davidson (1983). In the initial sentence, both groups make proportionately more regressions in the more difficult Late Antecedent condition (F1 (1,24) = 5.68, $p < .02$; F2 (1,28) = 7.58, $p < .01$). It is interesting to note that

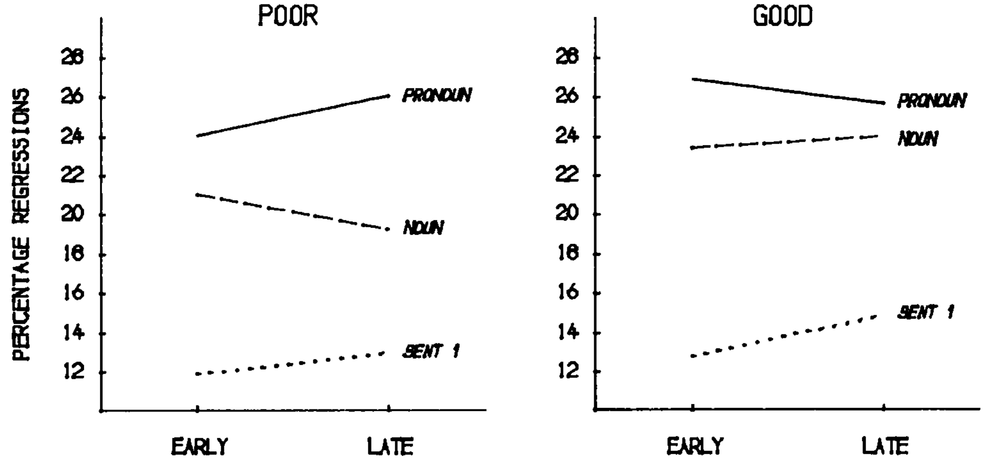

Figure 5. Regressions as a Percentage of Total Number of Fixations in Sentences and Questions

Poor readers do not (as is often claimed) make proportionately more regressions. In questions, a surprisingly large proportion of fixations are regressive (nearly twice as many as in the sentence), presumably reflecting the reader's attempts to locate relevant information in the presented text. Good readers show no reliable differences in the proportion of regressive fixations made among the four conditions, although again they do exhibit a (nonsignificant) tendency to make a greater proportion overall than poor readers. In contrast, Poor readers make a significantly greater proportion of regressions when dealing with pronominal rather than noun phrase anaphors ($F1\ (1,12) = 15.41$, $p < .01$; $F2\ (1,28) = 18.52$, $p < .001$). The apparent tendency for this difference to be greater following Late Antecedent sentences is not significant.

These results alone do not clearly support the account given above of differences in reading style between the two groups, however, the measure of overall proportion of regression masks important differences in the type of regressive eye movement readers may deploy. Two subclasses of regressive eye movements are of particular significance. These are: (1) Large Regressive Saccades (LRS), defined as left-going saccades more than 14 character spaces in extent and followed by a right-going saccade; and, (2) "Backtracks", sequences of three or more right-to-left saccades. The first of these measures provides an index of the reader's ability accurately, and selectively, to locate and reinspect regions of text outside the current focus of attention. Despite claims to the contrary (e.g. Monk, 1985), it appears that fluent readers make use of fixations of this kind, particularly when dealing with complex text (Kennedy, 1983; Kennedy and Murray, 1984). Measured LRS might therefore reasonably be expected to relate to the reader's level of competence. Backtracks represent a more cautious strategy in which the final fixation (i.e. the point at which the effective regression as a whole terminates) is located only after the inspection of a varying number of intervening words. The process presumably indicates that the reader is unaware of the exact physical location of the target information. The contrast between LRS and Backtracks in the reader's behaviour captures the distinction between 'explorers' and 'plodders' discussed by Kliegl (1982).

Figure 6 shows the number of backtracks made by Good and Poor readers, Since this measure refers to sequences of regressive saccades (and each backtrack comprises a number of fixations) it is not reasonable to treat it as a proportion of the total number of regressive saccades.

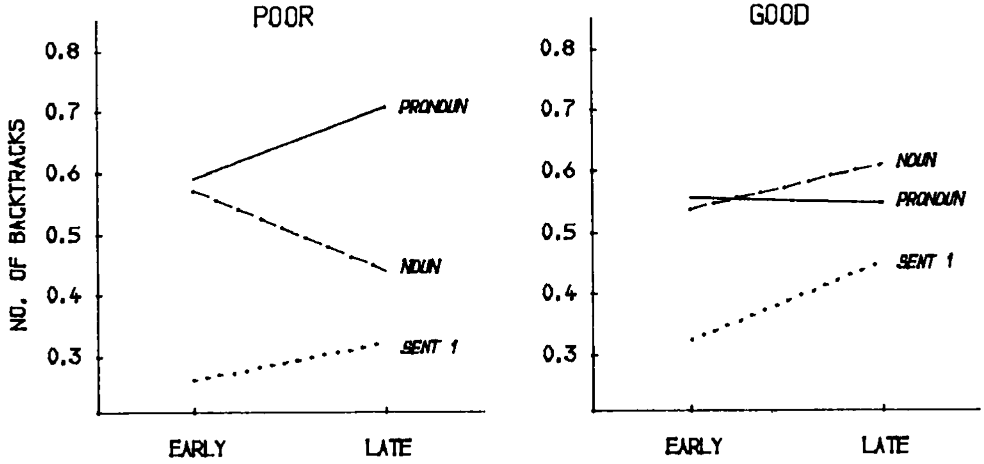

Figure 6. Number of Backtracks in Sentences and Questions

In the initial sentence both Good and Poor readers show an equal tendency to make more backtracks in Late Antecedent sentences. Backtracks recorded while subjects responded to questions mirror the pattern of results from regressions as a whole (Figure 5). The Good group show no variation between conditions. As predicted, however, the Poor group make many more backtracks in questions containing pronominal anaphors (F1 (1,12) = 11.14, $p < .01$; F2 (1,28) = 9.45, $p < .01$), and there is a tendency for this difference to be greater following Late Antecedent sentences (F1 (1,12) = 6.98, $p < .02$; F2 (1,28) = 3.80, $p = .06$).

Figure 7 shows the number of Large Regressive Saccades as a proportion of the total number of regressions made (since these are single events in the record). LRS events are comparatively rare and there was considerable variability in the data. However the results allow some broad generalization to be made. As predicted, there is a reliable trend overall for Good readers to make more regressions of this type than Poor readers (F1 (1,24) = 4.24, $p < .05$; F2 (1,28) = 5.74, $p < .05$). For Poor readers there is no evidence at all of any variation in LRS as a function of the experimental manipulations. The apparent interaction between Position of Antecedent and Type of Anaphor shown by Good readers is consistent with our predictions, but fails to achieve statistical significance.

CONCLUSION

The results presented here, taken together, argue for an analysis of Reading Time in terms of at least three components: (1) the duration of fixations; (2) the number of fixations; and (3) the duration of blinks. There is clear evidence that each of these may bear a different functional relationship to text variables. The examination of readers of varying ability illustrates well the problems of interpreting Reading Time. Good and Poor readers appear to modulate the number and duration of fixations and the duration of blinks in different ways when

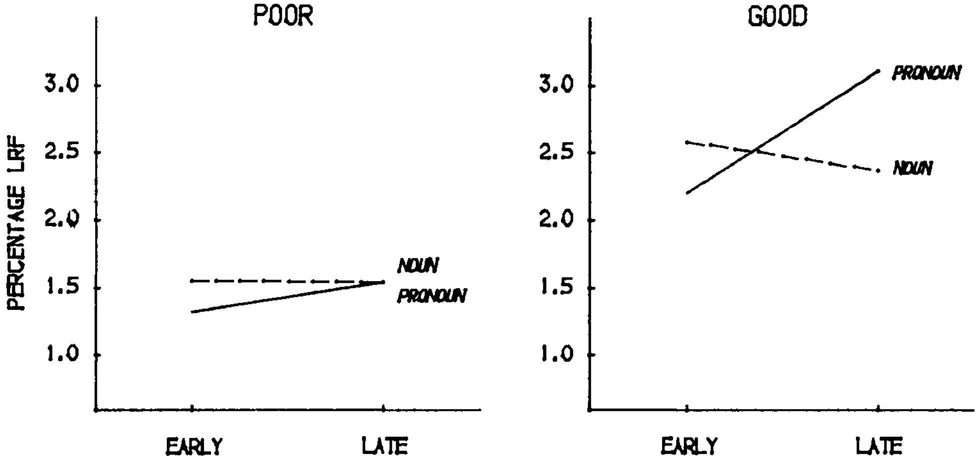

Figure 7. Large Regressive Fixations as a Percentage of Total Number of Regressions

faced with the same text. These differences in reading style can be readily interpreted, but may well be masked in a measure of global reading time.

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EYE MOVEMENTS: From Physiology to Cognition
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EYE MOVEMENTS AND LEXICAL AMBIGUITY

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Readers' eye movements were recorded as they read sentences containing lexically ambiguous words. With a neutral preceding context, readers fixated longer on ambiguous words with two highly likely meanings than on ambiguous words with a highly dominant interpretation. However, when the disambiguating information was consistent with the non-dominant interpretation, readers had much more difficulty processing the rest of the sentence when the ambiguous word had a highly dominant interpretation than when it did not. With biasing preceding context, the pattern of results suggested that differential fixation times on ambiguous words reflects post-lexical selection and integration processes.

INTRODUCTION

Recently there has been considerable debate and controversy concerning the extent to which eye movement data accurately reflect cognitive processes during silent reading. In particular, the central issue is whether or not the amount of time that a reader looks at a given word reflects the processing associated with comprehending that word. While the average duration of an eye fixation is 200-250 ms, there is considerable variability in the duration of any single fixation for a given reader (Rayner, 1978). Fixation durations range from 100 ms to over 500 ms even for fairly simple text. To what extent does this variability reflect moment-to-moment processing activities? At one extreme, some have argued that the variability is merely an epiphenomenon (Ward & Juola, 1982). Others have argued that there is a rather tight link between cognitive processing of the text and the amount of time that a reader looks at a given word (Just & Carpenter, 1980; Rayner, 1977; 1978).

There is now a fair amount of evidence to indicate that some of the variability is due to systematic differences in the ease of processing the words in the text. For example, words that are constrained by or predictable from the context receive shorter fixations than do words that are not constrained by or predictable from context (Ehrlich & Rayner, 1981; Zola, 1984). Likewise, words that are frequently used receive shorter fixations than infrequent words (Inhoff, 1984; Just & Carpenter, 1980; Rayner, 1977), even when word length is controlled for (Rayner & Duffy, 1986). Finally, the grammatical category of a word can influence fixation time since the main verb in simple declarative sentences receives longer fixations than do subject or object nouns (Rayner, 1977; Holmes & O'Regan, 1981). These pieces of evidence all suggest that much of the variability in fixation times during reading is due to the ease (or difficulty) with which certain words can be processed. It is also clear that a number of other factors can influence the amount of time that a word is looked at. These other factors include the minimal oculomotor reaction time of the eyes (Rayner, Slowiaczek, Clifton, & Bertera, 1983), parafoveal preview effects (Rayner, 1975; Balota, Pollatsek, & Rayner, 1985), syntactic parsing effects (Frazier & Rayner 1982; Rayner, Carlson, & Frazier, 1983), and higher order semantic integration effects (Ehrlich & Rayner, 1983; Just & Carpenter, 1980).

These results lead us to be optimistic about the use of eye movement data to study language processes during reading. Just and Carpenter (1980) proposed that all of the processing associated with a given word is completed before the eyes move to a new word. While we suspect that many processes associated with lexical access and syntactic parsing are completed prior to the eyes moving to the next word, data we have collected lead us to believe that not all processing associated with a word is completed before the eye movement. In large part, this belief stems from the fact that spillover effects have been documented in which we have shown that characteristics of the word encountered on fixation n spillover onto fixation n+1 (Ehrlich & Rayner, 1983; Rayner & Duffy, 1986). Thus, while fixation time on a word may not be a perfect reflection of the processes associated with comprehending a word, we believe that careful investigations using eye movement data can reveal interesting information concerning language processing during reading.

In the present paper, we describe some experiments that we have recently completed examining the effect of lexically ambiguous words on fixation times in reading. Our basic strategy was to present sentences to subjects that were identical except for a given target word that was either lexically ambiguous or was a control word matched to the ambiguous word in relevant ways. We then examined the duration of the first fixation on the target word, as well as the gaze duration (which is the sum of all fixations on the word prior to an eye movement away from the word), to determine what effect lexical ambiguity has on the amount of time the reader pauses on a target word.

Current evidence (Seidenberg, Tanenhaus, Leiman, & Bienkowski, 1982; Swinney, 1979) strongly suggests that multiple meanings of a lexically ambiguous word are accessed when such a word is encountered even when the context makes it clear which sense is appropriate. If multiple access occurs, then it may make processing more difficult by increasing the difficulty of lexical access or by increasing the difficulty of integrating the word with the rest of the text following lexical access. To determine if readers look longer at ambiguous words, we asked subjects to read sentences such as:

(1) He saw the boxer (puppy) was barking at the cat.

(2) He put the straw (wheat) in the barn for the cows.

Each sentence contained either an ambiguous noun or an unambiguous control word (in parentheses in the examples). The ambiguous word and its matched control word were equated for frequency and length. The control word (and subsequent sentence context for the ambiguous word) generally corresponded to the less dominant meaning of the two senses for the ambiguous word. This was done intentionally since in prior research there has been evidence of clear increases in fixation times when the disambiguating information was encountered (Frazier & Rayner, 1982). We examined fixation times not only on the target words themselves as a function of ambiguity, but also on the disambiguating information which followed. Fixation times on the word fixated prior to and after the target were also examined. For the word fixated prior to fixating on the ambiguous word (or its control), we found no differences between conditions. For the word fixated following the target word, we sometimes found significant differences due to spillover effects or because the word helped disambiguate the lexically ambiguous word. However, since our primary focus in this paper is on the lexically ambiguous words per se, data from the fixations prior to and after the target word will not be discussed further.

EXPERIMENT 1

In Experiment 1, sixteen college students read short sentences like those in examples (1) and (2) above. Eye movements were recorded by a Stanford Research

Institute Dual Purkinje Eyetracker which has a resolution of 10 minutes of arc. Viewing was binocular with eye location recorded from the right eye. The eye tracking system was interfaced with a Hewlett-Packard 2100A computer that ran the experiment. The position of the subject's eye was sampled every millisecond by the computer, and a determination of the location of the eye was made every four milliseconds. The text was presented on a Hewlett-Packard 1300A Cathode Ray Tube (CRT) which was also interfaced with the computer. The subjects' eyes were 46 cm from the CRT and three characters equalled 1 degree of visual angle. The characters were presented in lower-case (except for the first letter of the sentence and proper names) and were made up from a 5 X 7 dot matrix. The CRT was covered with a dark theatre gel so that the characters appeared very clear to the subjects.

The dependent variables in the study were (1) first fixation duration and (2) gaze duration. First fixation duration is the duration of the first fixation on the target word. If subjects made only one fixation on the target word, that value was entered into the mean score. If a subject made more than one fixation on a target word (this occurred about 20% of the time), only the first fixation duration was used to compute the mean. Gaze duration, on the other hand, is the sum of all of the fixations made on a target prior to any movement away from the target word. If the target word was not directly fixated (which occurred about 5% of the time), then the closest fixation within five characters to the left of the target word or one to the right was counted as the fixation during which the target word was processed.

There was no effect of ambiguity within either the analysis of first fixation duration or gaze duration. First fixation durations averaged 218 ms for the ambiguous target words and 220 ms for their controls; gaze durations averaged 251 ms for both conditions. However, further analyses of the stimulus items suggested an additional factor which might mask any effects in the data. The less likely meanings for the ambiguous lexical items varied in probability from fairly likely (generated by 48% of subjects in a norming study) to fairly unlikely (generated by 1% of subjects). It may be the case that both meanings of an ambiguous word cause processing difficulty only when the meanings are fairly equally likely (i.e., when the ambiguous word is equibiased). When one meaning is highly likely (the word is non-equibiased), the less likely meanings may not affect processing. If this is the case, then the lack of an effect for the ambiguous words may be due to the presence of a number of non-equibiased lexical items among the stimuli.

In a post-hoc test of this hypothesis, the eight ambiguous words were divided into two groups according to the degree of equibias. The less likely meanings for the four equibiased items had a mean probability of .38; the less likely meanings for the four non-equibiased items had a mean probability of .11. The mean gaze durations for these groups were 269 ms for the equibiased and 253 for their controls; 236 ms for the non-equibiased and 254 for their controls. While the number of items in each group is small, the pattern of means is consistent with the hypothesis. A second experiment was run as a further test of the hypothesis using a larger set of words.

EXPERIMENT 2

In Experiment 2, thirty-two college students participated as subjects. The apparatus and procedure was identical to the first experiment. Nine equibiased and nine non-equibiased ambiguous lexical items were chosen using the norms of Gorfein, Viviani, and Leddo (1982), Geis and Winograd (1974), and ratings we collected locally. The dominant meaning for the equibiased items had a probability range of .47-.67, with a mean of .58. The dominant meaning for the non-equibiased items had a probability range of .78-.98, with a mean of .87. Each ambiguous item was paired with an unambiguous control word matched for word length and frequency. The ambiguous items were ambiguous when encountered and disambiguated at the end of the sentence. The intended meaning was always the less likely meaning for the ambiguous word.

The experiment tested the hypothesis that processing is more difficult for equibiased ambiguous words compared with unambiguous controls, but not for the non-equibiased ambiguous words. This hypothesis predicts that mean fixation time for the equibiased items will be longer than for their controls; the times for the non-equibiased items will not differ from their controls. The data were scored as in Experiment 1. Three sets of means are presented in Table 1: first fixation duration and gaze durations on the target word and time spent on the disambiguating information.

Table 1
Mean first fixation and gaze duration (in milliseconds) on the target words (gaze duration is in parentheses) and mean time (in milliseconds per character) spent on the disambiguating region in Experiment 2.

	Fixation time on target word	
	Ambiguous	Control
Equibiased	237 (275)	229 (258)
Non-Equibiased	227 (260)	230 (263)
	Time spent on disambiguating region	
	Ambiguous	Control
Equibiased	76	64
Non-Equibiased	82	60

As originally predicted, subjects spent extra time looking at the ambiguous target items when the two meanings for the ambiguous item were fairly equally likely. This was not the case for ambiguous words for which one meaning was highly likely. One way to account for the interaction pattern would be to claim that both likely meanings are accessed for the equibiased ambiguous targets and that only the dominant meaning is accessed for the non-equibiased. If this is the case, then there are at least two possible sources of the additional processing time for the equibiased items. First, lexical access may take longer when two separate meanings for a word must be accessed in the lexicon. Second, following lexical access, the process of integrating the target word with the preceding context may take longer when this process has available as input two possible meanings. This account depends on the assumption that only one meaning is accessed for the non-equibiased ambiguous targets. Research using a cross-modal priming technique, however, suggests that even low dominant meanings of an ambiguous word are initially accessed when such a word is encountered (Onifer & Swinney, 1981).

Perhaps a more reasonable account of the interaction would claim that meaning dominance affects the post-access selection and integration processes. Recent research (Swinney, 1979; Seidenberg et al, 1982) strongly suggests that while all meanings of an ambiguous word are initially accessed, one meaning is quickly selected even in the absence of disambiguating context. This selection process may be more difficult for the equibiased ambiguous targets where the reader must decide between two equally likelymeanings. The selection may be much easier, and hence quicker, for the non-equibiased targets where one meaning predominates.

An analysis of the disambiguating region revealed that subjects spent longer reading the ambiguous versions than the controls. Furthermore, subjects spent longer on the non-equibiased ambiguous sentences than the equibiased. The analysis of the disambiguating region indicates that while the equibiased ambiguous items required additional processing time when first encountered, the non-equibiased ambiguous items required more time when finally disambiguated. There are two complementary reasons for this finding. First, it is reasonable to assume that the post-access selection process virtually always selected the dominant meaning for the non-equibiased ambiguous items. Since this meaning was always incongruent with the disambiguating information, a time consuming reinterpretation was required once the disambiguating information was encountered. Such a reinterpretation was probably required on almost all of the trials involving non-equibiased items. In contrast, if subjects randomly selected one of the two equally likely meanings for the equibiased ambiguous items, they were likely to select the inappropriate meaning on only about half the trials. Thus, fewer time consuming reinterpretations were required for the equibiased ambiguous target sentences. Second, when a reinterpretation was required, the speed with which the alternative meaning was re-accessed may be a function of its likelihood. The alternative meanings for the non-equibiased ambiguous items were much less likely than those for the equibiased and may thus have taken longer to reaccess when a reinterpretation was required.

EXPERIMENT 3

In Experiment 3, thirty-two subjects (different from those in Experiment 2) participated. In this experiment subjects read sentences containing lexically ambiguous words. However, rather than comparing ambiguous words to control words, we compared equibiased and non-equibiased lexically ambiguous words to each other. The target words were matched on frequency and other relevant variables. We also varied the distance between the target word and the disambiguating information. In the short distance condition, the disambiguating information came immediately after the occurrence of the lexically ambiguous target; in the long distance condition a phrase was inserted between the target word and the disambiguating information. Also, unlike the first two experiments, the disambiguating information was consistent with the dominant meaning of the target word half of the time. Eight equibiased and eight non-equibiased lexical items were chosen from norms collected locally. The dominant meaning for the equibiased items had a probability range of .51 - .62, with a mean of .57. The dominant meaning for the non-equibiased items had a probability range of .80 - .96, with a mean of .90.

As in Experiment 2, we found that subjects looked longer at equibiased ambiguous words than at non-equibiased words. Gaze duration was 281 ms for equibiased words and 248 ms for non-equibiased words. We found no effect of the distance between the ambiguous word and the disambiguating information. However, when the time to read the remainder of the sentence from the point of disambiguation on was examined, we found a significant interaction. These data are shown in Table 2. When the ambiguous word had two equally likely meanings, subjects read the remainder of the sentence when the disambiguating information was consistent with the dominant interpretation of the sentence a bit faster than when the rest of the sentence was disambiguated in the direction of the non-dominant meaning. On the other hand, when the target word was non-equibiased, it took much longer to read the remainder of the sentence when the disambiguating information was consistent with the non-dominant meaning than when it was consistent with the dominant meaning. Although the reading times in Experiment 3 are shorter than in Experiment 2, the pattern of results is very consistent. Exactly why the reading times differ is unclear, but it is probably due to both different subjects and sentences being used in the two experiments.

Table 2

Mean time (in milliseconds per character) spent on the disambiguating region in Experiment 3.

	Dominant	Non-Dominant
Equibiased	36	39
Non-Equibiased	36	55

The data from Experiment 3 basically demonstrate that when there are two fairly equally likely meanings of an ambiguous word (so that it is equibiased), subjects spend more time looking at the target word than when there is a highly dominant meaning for the target word. On the other hand, the amount of time that it takes to read the sentence from the disambiguating word on was considerably longer when the target word was a non-equibiased ambiguous word and the disambiguating information instantiated the non-dominant interpretation. In the case of equibiased targets, it did not matter too much whether or not the dominant interpretation was instantiated.

EXPERIMENT 4

In Experiment 4, sixteen subjects participated. This experiment was identical to Experiment 2 except that half of the time the disambiguating information preceded the target. As in Experiment 2, the disambiguating information was always consistent with the less dominant meaning of the two senses of the word for the non-equibiased targets; it was consistent with the more dominant meaning for the equibiased. For example, the sentences for the non-equibiased target word <u>boxer</u> were as follows:

(3) Last night the boxer (puppy) was miserable after its hind legs were injured in an accident.

(4) After its hind legs were injured in the accident, the boxer (puppy) was miserable.

Sentence (3) is similar to sentences used in the second experiment; a neutral context precedes the target word, and disambiguating information appears after the target word. In Sentence (4), on the other hand, the disambiguating information precedes the target word so that the appropriate meaning for the word is signalled in advance. Eighteen equibiased and eighteen non-equibiased lexical items were used. The dominant meaning for the equibiased items had a probability range of .48 -.69, with a mean of .57; for the non-equibiased items the range was .83 - 1.00 with a mean of .93.

Table 3 shows the results of the experiment. First, notice that the gaze durations in the condition in which a neutral context precedes the target word basically replicate Experiment 2: there was no effect of ambiguity for the non-equibiased targets and an effect for the equibiased targets. When the disambiguating information precedes the target word, the pattern was reversed. In contrast to the Neutral condition, the equibiased ambiguous targets were not faster than their controls. This seems to suggest that the difference in the Neutral condition (and in Experiment 2) was due to a post-lexical access integration process. The work of Swinney (1979) and of Seidenberg et al. (1982) suggests that both meanings of an ambiguous word are accessed in these disambiguated contexts as well as in the neutral contexts. If the effect in the Neutral condition is due

Table 3

Mean gaze duration (in milliseconds) on target word in the neutral condition and when disambiguating information precedes the target.

	Neutral Condition	
	Ambiguous	Control
Equibiased	267	245
Non-Equibiased	246	241
	Preceding Disambiguation	
	Ambiguous	Control
Equibiased	253	249
Non-Equibiased	270	248

to processing difficulty associated with accessing two meanings at the same time, then the effect should have been observed in the Disambiguated condition as well as in the Neutral. In fact the effect disappeared in the Disambiguated condition. This pattern is more easily accounted for by a hypothesis which claims that the effect in the Neutral condition is due to the difficulty of selecting among two meanings once they have been accessed. This post-access selection becomes much easier once disambiguating context is introduced; thus the effect is not observed in the Disambiguated contexts.

The claim that gaze duration on the target word reflects post-access processes is supported by the pattern of effects for the non-equibiased target words. Again, there was no effect for non-equibiased ambiguous targets in the Neutral condition, but these targets took longer than their controls in the Disambiguated condition. Readers presumably instantiate the dominant meaning upon access, ignoring the subordinate meaning. This meaning fits with the Neutral context; as a result there is no effect of ambiguity in the non-equibiased Neutral condition. In the Disambiguated condition, however, readers have selected the wrong meaning. The attempt to integrate this meaning with prior context is reflected in the longer gaze durations on the non-equibiased ambiguous targets in the Disambiguated condition. The effect in this condition provides converging evidence that some of the post-access selection and integration of meaning must occur during the initial gaze on the target word.

DISCUSSION

The experiments described here provide new information concerning the processing of lexically ambiguous words and further evidence concerning the usefulness of eye movement data to investigate cognitive processes during reading. First, at a substantive level our data provide clear information about the processing of ambiguous words. In the absence of prior contextual information specifying the appropriate interpretation of a word with alternative meanings, readers looked longer at a word with two likely meanings than a word with a highly dominant meaning or a control word matched for word frequency. In terms of fixation times on the target words, ambiguous words with highly dominant meanings were not looked at any longer than control words. However, when the disambiguating information was consistent with the non-dominant interpretation of the ambiguous word, readers required more time to complete reading the sentence when a non-equibiased word was present.

The pattern of gaze durations on the target words clearly suggests that low frequency meanings do not have the same status as high frequency meanings in the initial processing of an ambiguous word. While all meanings of a word may be accessed regardless of likelihood (Onifer & Swinney, 1981) these meanings may not all be equally available to the processing stages following lexical accesss (Simpson & Burgess, 1985; Simpson, 1984; Hogaboam & Perfetti, 1975). It may be the case, for example, that equally frequent meanings tend to become available to post-access processes at the same time, thus forcing a time consuming selection to be made. Infrequent meanings, on the other hand, may become available after post-access processes have begun working on the dominant meaning and thus may be ignored by these post access processes.

An issue which has been somewhat controversial in the literature is whether effects observed for a set of target words are due to lexical access processes or to post-access processes (see Balota et al, 1985; Ehrlich & Rayner, 1981). While there are good reasons to believe that characteristics of a target word and its context may affect lexical access processes (e.g., Ehrlich & Rayner, 1981), in the present studies it appears that the effect of ambiguity is best accounted for by post-access selection and integration processes. For the equibiased ambiguous words, selecting among two meanings once they are accessed is time consuming in the absence of disambiguating context. For the non-equibiased ambiguous words, attempting to integrate the dominant meaning with a context which is congruent with the subordinate meaning is time consuming.

Finally, the results of the present studies add to the growing body of evidence that attest to the fact that eye movements are a good reflection of cognitive processes during reading and that eye movement data can be used effectively to study language processing during reading. Our basic argument is that fixation times on a word may not be a perfect reflection of all of the processes associated with comprehending that word and that processes may spill over from one fixation to the next. Nevertheless, careful controlled experimentation using eye movement data as dependent variables can reveal a great deal about cognitive and language processing during reading.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

READING A TEXT: THE EFFECTS OF TYPOGRAPHY AND COGNITIVE PROCESSING ON EYE MOVEMENT STRATEGIES

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An experiment was conducted to investigate the effects of one perceptual and one cognitive factor on eye movement strategies during reading. On the first reading, the cognitive factor gave highly significant differences for the fixation duration, the number and the length of the regressions, but did not affect the progressions. On the second reading, the four parameters were significantly affected by this factor. The perceptual factor did not change the length of regressions during the first and the second reading, nor the number of regressions on the first reading but influences the other parameters. No interaction between the two factors was observed. These data suggest that the component processes involved function independently.

Research on eye movements in reading typically distinguishes the effects due to the perceptual characteristics of the text from the effects related to cognitive processing.

As early as 1905, Javal had studied the effect of the physical characteristics of the text showing how lighting conditions and lettering style could improve legibility. In 1955, Tinker and Paterson presented a complete review of the data in this field.

Since then, technical progress has provided us with more accurate eye-movement recording techniques allowing the estimation of saccade size in character units. In the normal reading situation, Spragins, Lefton and Fischer (1976), Fischer (1976) demonstrated that changing word shape, using small and capital letters, and changing the space between words affected fixation duration and saccade size. The original paradigm developped by McConkie and Rayner (1975) was used to demonstrate that changing word shape in peripheral vision modified the gaze duration.

More recently, Rayner (1983) established the relationship between perceptual span and oculo-motor parameters, whereas O'Regan, Levy Schoen and Jacobs (1983), studying the effects of visual span, showed that doubling the normal inter-letter interval decreased progressions and fixation durations.

The influence of cognitive processing is more difficult to evaluate, although ever since 1976 Just and Carpenter (1976, 1980 ; also Carpenter and Just, 1977) have repeatedly studied its influence on fixation duration. In 1980, they presented the results of an application of the regression model to the gaze duration on each word as a function of three processing stages (encoding and lexical access, case role assignment, interclause integration) and of each text component (topic, definition / cause / consequence, subtopic, expansion, detail). The results are integrated into a model in which gaze duration reflects the time to execute comprehension processes.

In parallel, several other authors carried out research on the processing of sentence structure, and in particular, Holmes and O'Regan (1981), Frazier and Rayner (1982) and Frazier (1983). This last study showed that the average duration of the three fixations following the disambiguation point of the sentence was significantly longer than the average of the preceding three fixations.

Rayner (1983) considers that information input is processed by the monitoring system during the first 50 ms and that the latency of eye movements is approximately 125-175 ms thereafter. It appears that the access of meaning and syntactic processing strategies occur during this time. Since fixations last on average between 225 and 450 ms , there remains a minimum of 50 to 225ms for the initiation of higher level cognitive processes. Moreover, cognitive processing may be at the origin of regressive saccades that allow the subject to check and/or complete information he has already read. The results obtained by Rossi and Ehrlich (1985), Ehrlich and Rossi (1986) are in agreement with this view.

It therefore seems clear that fixation duration and the size of progressive saccades are influenced by cognitive processing and by the perceptual characteristics of the text, whereas regressive saccades depend more on the activity of comprehension. Although Levy-Schoen (1983) suggests that care should be taken in making these kind of conclusions, she admits that the instantaneous adaptations that the eye makes are a reflectionof cognitive processes.

An adequate theory of reading involves the description of several processes: perceptual processes, word encoding, lexical access, syntactic parsing, semantic integration and text representation.

A central but very complex question that remains to be answered concerns the relations between these different processes: do they function independently of each other or do they interact with each other? Our experiment aims at providing a partial response to this question by studying the effects of one perceptual and one cognitive factor on eye movement strategies during reading. The perceptual factor is typography: the usual typography has constant letter spacing whereas the unusual typography has variable letter spacing because each letter is written inside a rectangle of fixed size even if the letters are narrow (e.g. "i"). This leads to an unstructuring of the word by modifying its shape, and to a doubling of the length of each line of text. The choice between these two typographies was discussed when display monitors were constructed for the french information system (Antiope).

The cognitive factor was manipulated by asking subjects to read a text in order to collect specific information. Some of the lines of text contained this information (relevant lines) and others contained information that was not necessary for task execution (non relevant lines). This factor is assumed to affect the semantic integration demands.

The variations in eye movement behavior for the different lines of text will be studied as a function of these two factors. If no interaction is observed between them, then it suggests that these two types of process function independently.

METHOD

Material

A 225-word text about a boat race was constructed. There were four boats "Excitable" (A), "Unbridled" (B), "Outrageous" (C), "Fiery" (D), all adjectives with similar meaning. The text had a title ("A Boat Race") and was composed of three paragraphs: an introduction (4 lines), a central paragraph (12 lines), a conclusion (5 lines). In the central paragraph, six sentences giving the relative positions of the boat at a first moment of the race and later at a second moment of the race were inserted among sentences describing the boats. These sentences were the relevant sentences in consideration of the reading task. They appeared in lines n°5, 7, 8, 12, 14, 16 which were named relevant lines. By contrast the other lines of the text were non relevant lines.

The text was printed on a sheet of paper. Two distinct typographies with lower case characters were used (cf. Table I). In the usual typography condition (group M1), the distance between the characters was constant and the text filled a 12 cm long x 7 cm wide rectangle. In the unusual typography condition (group M2), each character was printed in a fixed size frame whatever the width of the character. The frames were juxtaposed so that the distance between the characters was variable. For example, the distance between two wide letters m and w was smaller than the distance between i and j. Consequently, word shape was altered and line length increased by nearly 100%, the text filling a 22 cm long x 7 cm wide rectangle.

a - Usual : **Tous conserveront un merveilleux**

b - Unusual : Tous conserveront un merveilleux

Table I : Typographies

The text was presented on a vertical support 30 cm from the subject's eye.

Subjects were seated in a chair with their chin placed on a chin rest in order to minimize head movements. Eye movements were recorded by a photo-electric mechanism linked to a micro computer (Acorn BBC, model B). This recording procedure was developed by Y. Barbin (1982) and the researchers of the Groupe Regard (Coeffé, Humbert, Jacobs, O'Regan, 1985)[1]. This system only processes horizontal movements and records the direction and size of saccades and the position and duration of fixations for each line of text. The sampling rate of the system is 10 msec. Eye movements were monitored for the first 16 lines of text but not for the 5 lines of conclusion.

Procedure

1/ First of all, subjects read a practice text at their normal reading rate. The subjects had to read the text line after line with the possibility of rereading parts of the same line but not previous lines. The reading times for the practice text were used to form groups of subjects matched in terms of spontaneous reading speed.

2/ After this practice text, all the subjects were told to read a text about a boat-race for comprehension and that they would be required to answer questions following this text. A precise reading objective was given to the subjects: they were informed that after reading the text they had to judge if two or three propositions conveying the positions of the boats were true or false. For example: "Outrageous is in front of Fiery", stated explicitly in the text or "Excitable is in front of Unbridled" which required the subjects to make inferences.

These propositions to be checked were learned by the subject. After that, the subject read the text, and then answered either true or false to the propositions.

These three stages 1) learning of the propositions to be verified, 2) reading the text and 3) verifying the propositions, were repeated on two successive trials.

3/ After the second trial and without being allowed to refer to the text, the subjects were given a comprehension test: they ordered the boats, indicating the rank of each of the four boats at moment 1 and at end of the race.

The entire session lasted 50-60 minutes.

Design

A 2 (usual vs unusual typography) x 2 (relevant vs non relevant lines) x 2 (trial) factorial design was used with typography as a between-subjects factor (groups M1 and M2) and line and trial as within-subjects factors.

Subjects

One hundred adults from the university of Paris satisfying a course requirement served as volunteer subjects. All were native speakers of french and they had normal uncorrected vision. Because of failures of calibration, sixteen subjects were lost and data were computed from eighty four subjects.

RESULTS

Comprehension scores

Each subject's answer to the ordering of the boats, at two moments during the race, was compared to the expected ordering by using the Kendall T. After the scores were transformed, the theoretical scores varied from -6 to +6. The mean scores were 1.45 for group M1 and 1.23 for group M2, showing no typography effect ($t(1.72) = 0.15$).

It is worth noting that these comprehension performances were poor with a large dispersion ($s = 2.07$ and $s = 2.22$).

Reading times

The mean reading times for the complete text on trial 1 and 2 are 76.93 sec and 69.03 sec for group M1, 83.82 sec and 77.19 sec for group M2. The reading time was longer for the unusual typography (group M2); on trial 2, this increase is 10%. The reading time was shorter on trial 2 than on trial 1. The means were submitted to a 2 (typography) x 2 (trial) analysis of variance. The two main effects were significant $F(1,61) = 5.80$, $p < .025$ and $F(1,61) = 38.60$, $p < .0005$. The interaction was not significant.

Eye movement parameters

For each subject and each line of text, four parameters were computed: (1) the fixation duration (msec) per character space, which is the total of fixation durations divided by the number of character spaces (2) the number of progressions for 100 character spaces (3) the number of regressions for 100 character spaces and (4) the mean regression size. Mean values were computed for relevant lines and for non relevant lines. Data were submitted to an analysis of variance.

The fixation durations are shown in Figure 1. For trial 1 and for trial 2, the fixation duration was significantly longer:

- with the unusual typography (M2) than with the usual one (M1);
- on the relevant lines (L1) than on the non relevant ones (L2).

On trial 2, the increase due to the typography factor was 19% and that due to the line factor was 35%.

There was no interaction between the typography and line factors.

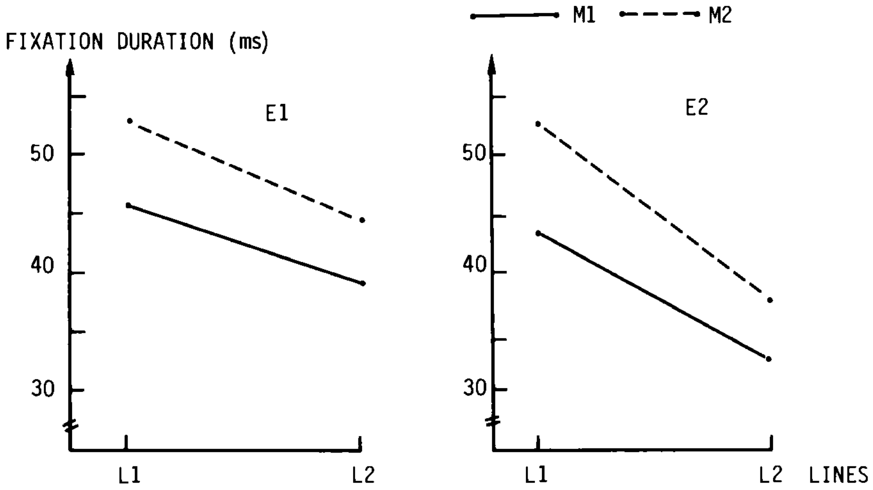

Figure 1
Fixation duration (ms) per character space for relevant (L1) and non relevant (L2) lines with usual (M1) and unusual (M2) typographies, for trial 1 (E1) and trial 2 (E2).

- The number of progressions (cf. Figure 2) was significantly higher in group M2 than in group M1, on trial 1 and 2. On the other hand, it was higher on relevant lines on trial 2, but not on trial 1. No interaction between the two factors was observed.

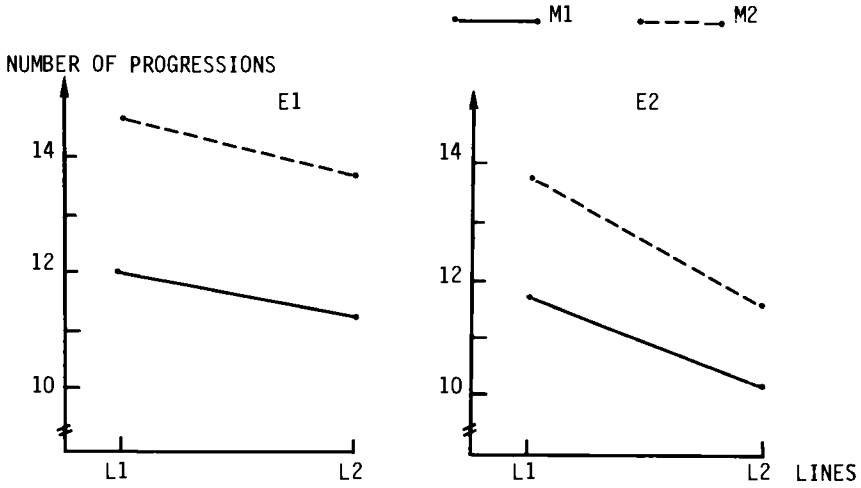

Figure 2
Mean number of progressions for 100 character spaces for relevant (L1) and non relevant (L2) lines with usual (M1) and unusual (M2) typographies, for trial 1 (E1) and trial 2 (E2).

The unusual typography (M2) increased the number or regressions (cf. Figure 3) on trial 2 but not on trial 1. It did not change the regression size. On the relevant lines (L1), the regressions were more frequent and longer than on the non relevant lines, on trial 1 and also on trial 2. The F values were highly significant.

For the two parameters, no interaction between the typography and line factors was observed.

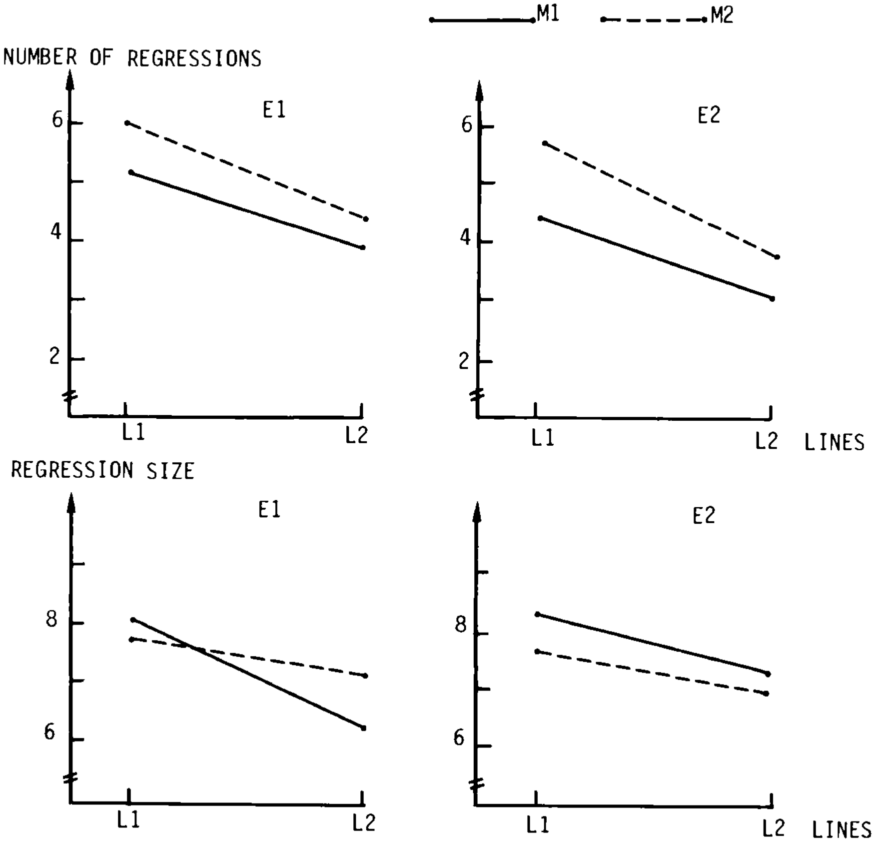

Figure 3
Mean number of regressions for 100 character spaces and mean regression size for relevant (L1) and non relevant (L2) lines with usual (M1) and unusual (M2) typographies, for trial 1 (E1) and trial 2 (E2).

In brief, these data show that the physical and cognitive characteristics of the text influence eye movements in a different way.

- On the first reading: the cognitive factor (relevant vs non relevant lines), gave highly significant differences for the fixation duration, the number and the length of the regressions but did not affect the progressions. The perceptual factor, typography, affected fixation duration and the number of progressions but not the number nor the length of regressions. The two factors produce similar effects on fixation duration and different effects on the way the lines of the text were scanned. No interaction between the two factors was observed.

- On the second reading: the cognitive factor gave significant differences for the four parameters: a 35 % change in fixation duration, 16 % in number of progressions, 21 % and 11 % in number and length of regressions. The perceptual factor yielded significant differences for three parameters and did not change the length of regressions. As for the first reading, no interaction between the two factors was observed.

DISCUSSION

The aim of this experiment was to investigate whether the component processes involved in reading function independently or interact with each other. More specifically, our experiment studied the interaction of perceptual processes (word encoding) and semantic integration.

The results clearly indicate that the use of an unusual typography that disturbs word shape makes word encoding more difficult and increases the processing time of each line of text. In this unusual typography condition the subject makes more progressive saccades than normal. However, although the length of each line of text is increased by nearly 100% (from 12 to 22 cms) the number of progressions only increased by 21% on the first reading and by 15% on the second. This implies that the subject adapted to the unusual typography condition by executing more saccades and above all by increasing saccade size (in angular terms).

Thus, as Rayner (1983) and O'Regan, Levy Schoen and Jacobs (1983) have pointed out, the progression size and consequently their number depend on the physical characteristics of the message.

It is only on the second trial that we observe an increase in the number of regressions. This data cannot be interpreted without referring to the modification of progressions caused by the increase in line length. In order to do this we calculated the proportion of regressions compared to progressions to give an indication of the number of regressions executed for each progression. This proportion is little affected by a change from usual to unusual typography. That is why it is possible to conclude that graphic changes in the lines did not affect the regressions.

In conclusion, perceptual processes and word encoding influence fixation duration and the number and size of progressive saccades.

The greater semantic integration demands involved in the processing of relevant lines forces the subject to increase fixation duration in the first reading and the second reading where a large effect is found (35 %). We also observe, as early as the first reading, an increase in the number and size of regressions. Thus the subject often goes back over parts of the line to help him in the semantic processing necessary for the task. On the other hand, the number of progressions only increased on the second reading. This increase is entirely due to large size regressions.

Overall, although the two factors produce different effects on saccades - the typography factor affecting mostly the progressions and the cognitive factor affecting above all the regressions - the two factors do have a similar influence on fixation duration. This data suggests that the component processes involved in the present experiment function independently.

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FOOTNOTES

(1) We would particularly like to thank A. Jacobs who adapted the recording procedure to our experiment.

OCULAR DOMINANCE AND READING AND SPELLING REASSESSED*

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This study examines the relationship between a new test of ocular dominance and reading and spelling ability in a group of schoolchildren. The test determines whether the child has a 'fixed' reference eye or whether they have unfixed ocular dominance. Previous research on children referred to a clinic for reading disorders suggested an association between specific reading disorders and unfixed ocular dominance . (Stein and Fowler, 1982).

In this study 323 schoolchildren with a mean age of 8.5 years were assessed on three aspects of reading skill. Spelling was assessed by means of the Schonell Graded Word Spelling Test. Single word reading by the Schonell Graded Word Reading Test and the reading of prose material by the Neale. In addition each subject received a full intellectual assessment by means of the WISC-R.

Ocular dominance was assessed by means of a modified form of the 'Dunlop Test'. This test determines in which eye the ocular motor and retinal signals are associated thus distinguishes the dominant eye.

The subject's reading and spelling abilities were considered in relation to their intellectual performance by dividing them into four groups using a separate analysis for verbal and performance mental age. The groups comprised those with reading or spelling difficulties whose spelling or reading was 18 months or more behind the relevant intellectual measure, superior readers or spellers whose reading or spelling was 18 months or more in advance of their intellectual age and two groups whose reading and spelling was within 17 months of their intellectual age.

The analysis of spelling performance in relation to both verbal and performance mental age failed to indicate any association between unfixed ocular dominance and spelling difficulty.

In comparing these findings to previous research it is apparent that no discrepancy exists between the proportion of 'dyslexics' who have unfixed ocular dominance. Stein and Fowler (1982) report 52% and 63% of 'dyslexics ' to have unfixed ocular dominance. The percentages found in this study are similar (see Table 1). It is in the control subjects where the discrepancy lies. Stein and Fowler report only one out of eighty control subjects to have unfixed ocular dominance. In this study a considerable percentage of subjects whose reading or spelling was 18 months or more in advance of their intellectual age had unfixed ocular dominance (see Table 2).

One possible reason to account for the discrepancy between this and the previous study is that in this study the test of ocular dominance was performed in the absence of any knowledge of the subject's intellectual or reading performance. It is concluded on the basis of the findings in this study that the modified Dunlop test is not on its own associated with specific reading or spelling difficulties in schoolchildren.

NUMBER AND PERCENTAGE OF SUBJECTS WITH SPECIFIC READING OR SPELLING DISORDERS AND UNFIXED OCULAR DOMINANCE

18 MONTHS BEHIND IN:	RELATIVE TO:	
	Verbal Mental Age	Performance Mental Age
Spelling	46 (49.5%)	100 (50.0%)
Single Word Reading	38 (43.2%)	95 (50.5%)
Prose Reading	17 (43.6%)	75 (52.4%)

TABLE 1.

NUMBER AND PERCENTAGE OF SUBJECTS WITH SUPERIOR READING OR SPELLING AND UNFIXED OCULAR DOMINANCE

18 MONTHS AHEAD IN:	RELATIVE TO:	
	Verbal Mental Age	Performance Mental Age
Spelling	11 (45.8%)	12 (44.4%)
Single Word Reading	14 (41.2%)	12 (46.2%)
Prose Reading	19 (38.0%)	19 (52.8%)

TABLE 2.

* This research was supported by a generous grant from the Linbury Trust

READING EYE MOVEMENTS OF PATIENTS WITH HOMONYMOUS HEMIANOPIA

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INTRODUCTION

The purpose is to analyze the qualitative and/or quantitative changes of the oculomotor scanning behaviour in reading when visual information is available only in one hemifield as it is for hemianopic readers. Are there specific compensatory eye-movement strategies in reading in the case of right or left hemianopia ? Are these changes correlated with elementary oculomotor disorders, neuropsychological impairment or to the localization of brain lesions ?

METHODS

Subjects : . control group : 20 adult normal french readers, without neurological or visual deficits and without history of developmental dyslexia.

. hemianopic group : 30 brain damaged patients with homonymous hemianopia (14 right : RHH, 16 left : LHH).

Eye movement study :

The elementary eye movements : saccades, smooth pursit and O.K.N. as well as the reading eye movements were recorded by EOG.

The oculomotor scanning behaviour was studied while reading a text of 209 words, 14 lines and 3 paragraphs with basic lexical and syntactic structures.

RESULTS

The reading eye movements of the control group were in accordance with the classical "staircase pattern".

In the hemianopic group this "staircase pattern" is recognizable only in eight patients.

QUALITATIVE CHANGES IN READING EYE MOVEMENTS OF HEMIANOPIC PATIENTS

According to the organization of their reading eye movements three main types of changes were defined in reference to the classical pattern evidenced by the control group.

	RHH (n = 14)	LHH (n = 16)
Disorganized	6 *	3 **
Moderately impaired	2	10
Preserved staircase pattern	5	3

* In 4 patients, the neuropsychological testing evidenced a pure alexia.
** All 3 patients had a severe unilateral agnosia.

R.H.H. Eye movements in reading

Disorganized (n = 6)

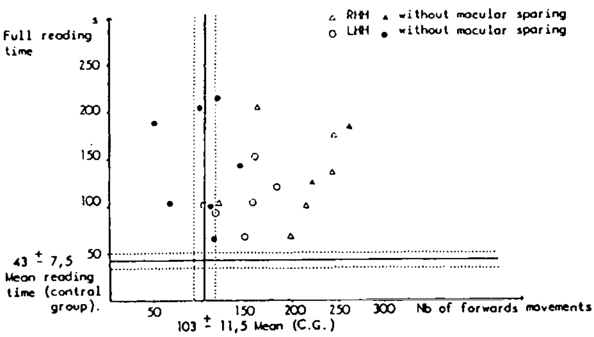
Preserved staircase pattern (n = 5)

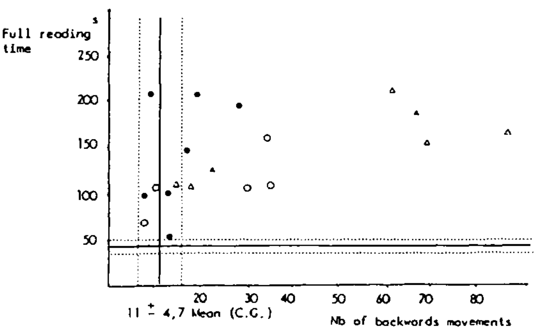
L.H.H. Eye movements in reading

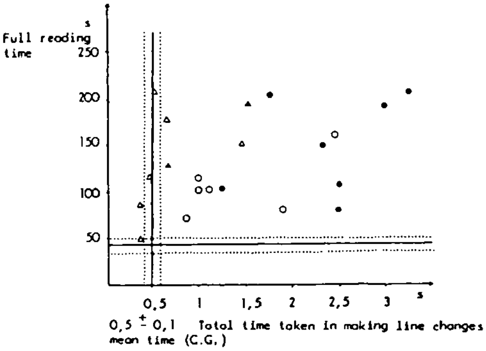
Disorganized (n = 3)

Moderately impaired (n = 10)

QUANTITATIVE CHANGES







DISCUSSION

A right visual defect disturbs the reading eye movements more severely than a left visual defect.

The impairment of the oculomotor behaviour in reading due to RHH is more severe, since the saccadic movement to right side is abolished (n = 3) or strongly disorganized. Whereas all patients with pure alexia have disturbed eye movements, this is not the case of aphasic dyslexia.

In the case of LHH the saccadic movements are more often disturbed than in RHH : abolished in 6 cases, strongly disorganized in 5 cases. This impairment of saccadic movements is not correlated to neuropsychological findings, as hemineglect and the disturbance of reading eye movements in LHH seemed to be due to oculomotor disturbance itself rather than to spatial agnosia.

OBLIQUE OCULAR MOVEMENTS IN MAN AND THEIR FLEXIBILITY.

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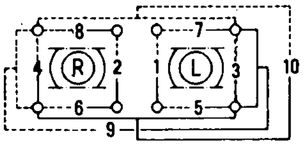
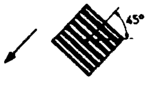
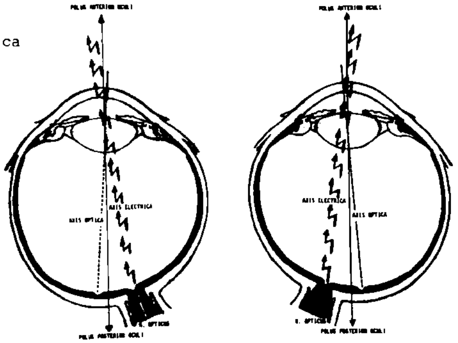
Electrooculographic (EOG) studies of oblique eye movements in 1400 children and normal and pathological adults showed an evolution in man. In oculocephalic interdependence there are four main stages at which oculomotor flexibility is indispensable: learning to walk, visual observation of the child's surroundings, learning to read, and old age or disease. There are two possibilities: oculocephalic dissociation or association.

Axis bulbi; axis optica; axis electrica of each eye.

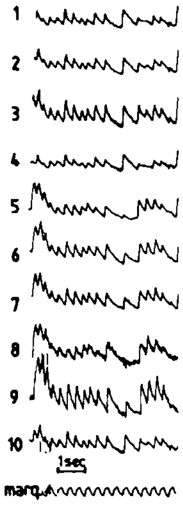
The periocular electric field is due to 2 generators. Each eye has an electric axis and these axes are not parallel.







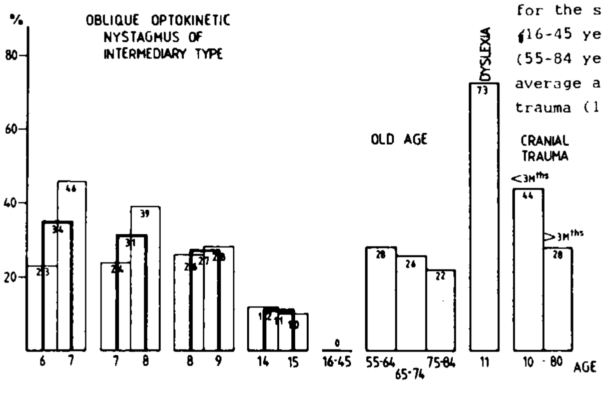
In electronystagmographic tracings with the same OPK stimulation 3 distinct types of oblique response appear which we have called rectilinear, rotatory and intermediate types.



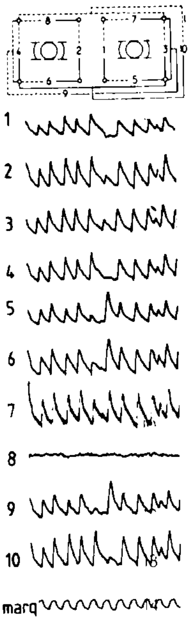
EOG tracing with 8 monocular and 2 binocular leads placed as in diagram with left-downward OPK stimulation.

Oblique right-upward OPK response of intermediate type. Monocular torsion. The left electric axis goes toward the back of the orbit and the right electric axis is tilted toward the roof of the orbit. The electric axes are parallel. The record with multiple monocular leads shows deflections of the same amplitude on all channels.

Distribution of OPK oblique nystagmus of intermediate type in schoolchildren (6-15 years, October and June and average for the school year), adults (16-45 years), older patients (55-84 years), dyslexics (average age 11), cranial trauma (10-80 years).

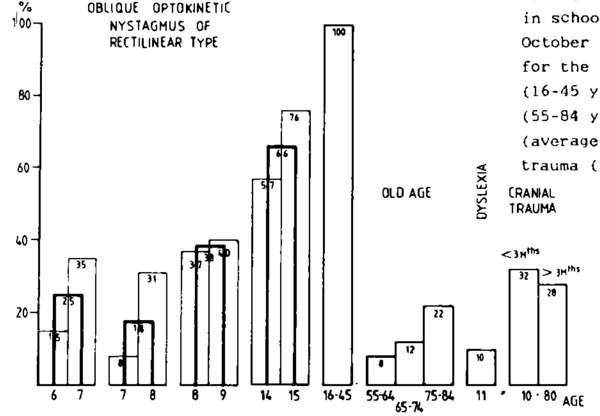


Oculocephalic dissociation is most clearly seen in learning to walk because the counterrolling of the eyes is at its most sensitive, and learning to read because the eye tends to move without cephalic participation.

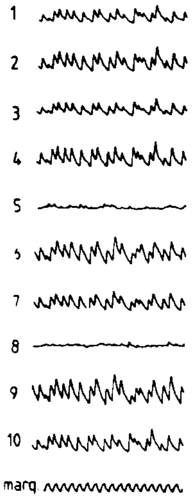


Eog tracing with 8 monocular and 2 binocular leads placed as in diagram. Left-downward OPK stimulation gives an oblique right-upward OPK response of rectilinear type. The electric axes go toward the back of the orbits which are not parallel. The vectors of each electric field enable us to describe the surface as resembling a truncated cone. The cross-section is an ellipse not a circle. The record with multiple monocular leads gives one isoelectric line.

Distribution of OPK oblique nystagmus of rectilinear type in schoolchildren (6-15 years, October and June and average for the school year), adults (16-45 years), older patients (55-84 years), dyslexics (average age 11), cranial trauma (10-80 years).

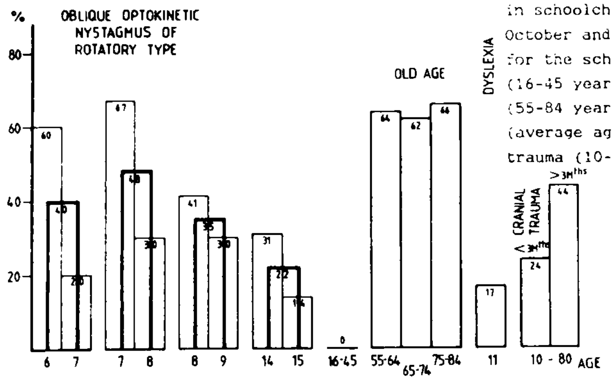


Oculocephalic association appears most distinctly in the child as he observes his environment visually and in adults over 50 or in pathological subjects when it is necessary to raise the oculovestibular nystagmogenic threshold to diminish pathological vestibular sollicitation.



EOG tracing with 8 monocular and 2 binocular leads placed as in diagram. Leeft-downward OPK stimulation gives an oblique right-upward OPK response of rotatory type. The result of the simultaneous torsion of both eyes in the same direction (intorsion in one eye and extorsion in the other). Electric axes are tilted in opposite directions. They will now be oriented toward the roof of the orbit of one eye and toward the floor of the other orbit. The record with multiple monocular leads gives 2 isoelectric lines.

Distribution of OPK oblique nystagmus of rotatory type in schoolchildren (6-15 years October and June and average for the school year), adults (16-45 years), older patients (55-84 years), dyslexics (average age 11), cranial trauma (10-80 years).



Conclusion: We have seen a gradual transformation in children from rotatory through intermediate to predominantly rectilinear types of oblique eye movements characteristic of adults. An evolution occurs in reverse in old age, prefigured by the abrupt modification after cranial trauma.

EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

EYE MOVEMENT RECORDING IN ERGONOMICS AND APPLIED RESEARCH

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1. INTRODUCTION.

In recent years research interest in perceptual and cognitive aspects of work has continued to grow due mainly to the introduction of new technologies into all areas of working life. This interest, accompagnied by the development of eye movement recording techniques, has encouraged eye movement parameters to be used in ergonomics studies. The number of publications where eye movements have been reported has also increased; this has led a number of authors to review the appropriateness of eye movement recording in psychology and ergonomics (Levy-Schoen (1983), McConkie (1981), Pailhous (1970)). Research workers continue to show a strong interest in eye movement recording and it seems opportune to take stock of the advantages and difficulties of using eye movement indices and evaluate the practice of eye movement recording in field studies.

The papers and posters contributed to the present symposium cover a range of applied research areas, such as ergonomics, sports research and radiological analysis. The techniques employed in the papers to study information processing include occlusion techniques and direct observation, as well as eye movement recording. The papers not only present recent studies where eye movements are reported but have also considered methodological questions concerning their use in applied research such as :

- the use of eye movement recording in favour of other techniques for studying information processing;
- the technical criteria involved in choosing an eye movement recording method;
- the eye movement parameters appropriate for the analysis of complex tasks carried out in "natural" situations;
- the difficulties in relating eye movement parameters to the underlying cognitive processes studied in applied research contexts.

2. Analysing complex tasks in a "natural" environment.

The investigator recording eye movements with a subject working at a complex task in a "natural" situation is confronted with additional problems to those normally met in the laboratory. A "natural" setting, an industrial workplace or a sports field, is not a constructed environment and the investigator has little or no means of controlling the different factors making up this environment. An important step in applied research, especially in ergonomics, involves analysing the situation under study to determine the subject's sources of information and the types of response used during the task. The goal of eye movement recordings at this stage is essentially directed towards an initial observation of the interaction between the subject and the task.

A "natural" setting is a very complex environment, compared to the laboratory where in principle the independant variables are controlled and the subject's responses are limited and known. The complexity of a "natural" environment can render a single interpretation of the data unviable as this would assume that the influence of the multiple variables were understood in terms of the different psychological processes employed to carry out the task.

Eye movement or point of regard recording provides a technique for following moment to moment processes of visual information acquisition during a task. Other techniques are available for studying the ongoing cognitive activity of the subject by recording intermediate responses prior to the availability of task output (Russo (1978)). These techniques include verbal protocol methods and certain computer controlled display techniques. In tasks where the acquisition of visual information is associated with a spatially structured environment, eye movement data can contribute to the analysis of underlying cognitive strategies employed in the task.

3. Choice of recording technique.

The technical problems involved in using eye movement recording equipment in "natural" situations are slowly being resolved with the development of head mounted point of regard recorders and computer based oculometers. However, it is still safe to say that there is a direct trade-off between the measurement precision and interference with the subject. Young and Sheena (1975) provide a table for comparing different methods using both technical criteria and considerations of acceptability by the subjects. Ideally the type of equipment used in applied research should be chosen after taking into consideration both the level of precision necessary to answer questions posed by the particular study, and the special problems associated with "natural" environments (notably subject acceptance of the equipment and the necessity for minimum interference with the observed behaviour). Mackworth (1976) has remarked that researchers can be sidetracked into using sophisticated methods of recording which can lead to a neglect of the theoretical questions under consideration. Often direct observation of where the subject is looking provides sufficiently useful data. It would appear that the effort involved in eye movement recording and analysis does not always justify the investment.

4. Interpreting different visual search parameters.

Interpreting data from eye movement recordings in field studies is limited by the control the investigator has on the information available to the subject. Eye movement recordings provide a means of determining what information could be visually collected and in what sequence. However, there is not necessarily a one to one relationship between fixation point and information acquisition. The ability to use peripheral vision in exploratory visual search is not completely understood and recording data on fixation points in space cannot indicate where information has been taken from within the useful visual field. The sequential organisation of fixation points does not necessarily reveal the mental activity of the subject. Scanpaths have been studied in various contexts but have only rarely been shown to be stable within subjects or comparable between subjects. The difficulties encountered when attempting to infer the mental processes involved in elementary tasks from eye-movement recordings are augmented when describing strategies of cognitive processing in complex tasks where the experimenter has little control over the environment.
The most common parameters used in eye movement recording in field studies include:

- number of fixations required to carry out a particular task;
- the spatial distribution of fixations over the visual field;
- the sequence of fixation points;
- the interval between fixations on the same point of interest in space;
- fixation times.

The number of fixations over a given period of time can be used as a global index of the information acquisition function of a task.
The relative frequency of fixations to different points in the visual field can indicate which sources the subject finds most important for the task. In some cases it is possible to rank the points of interest in order of importance.
The sequence of fixation points provides probably the richest set of indices; especially when coupled with other information about the task. For example, specific short sequences of fixations can reveal when the subject has to compare two sources of information or use two sets of information to deduce a third.

Most studies report statistics on fixation times during different phases of the task. Variations in mean fixation times have been shown to be related to task factors, subject characteristics, and the physical properties of the stimulus. It is assumed that fixation times provide some estimate of the time taken to decode, transmit and process visual information. However, in a complex task, the factors which can influence fixation times can vary over time, and mean fixation times should be treated as a very global index.

5. Conclusion.

The interpretation of eye movement data recorded from subjects carrying out complex tasks is not a trivial problem. The way information acquired from a particular fixation contributes to the underlying ongoing cognitive processes is not always apparent. In the analysis of complex "natural" tasks, investigators have no choice but to deal with the multiple sources available to the subject in order to determine the various strategies he can employ to carry out the task. It is often necessary to make use of various sources of information when working on field studies; eye movement recordings, performance data and recordings of other types of response, as well as data from task analysis all contribute useful information for the study of the subject's cognitive processes.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

IS THE ANALYSIS OF EYE MOVEMENT RECORDING A SUFFICIENT CRITERION FOR EVALUATING AUTOMOBILE INSTRUMENT PANEL DESIGN ?

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Most researchers agree that vision is the one human sense which is absolutely essential for driving. It is thus surprising to find that very little importance is placed on the analysis of eye movements in the design of automobile instrument panels, in spite of the introduction of new technologies for displaying information.
This paper tries to illustrate and discuss the advantages and difficulties of using eye movement indices in this domain and to describe some recent applied experiments.

INTRODUCTION

The development of microprocessors, new visual displays and communication techniques offers new ways to assist the driver in receiving and processing information. Thus, the display designer is faced with the problem of diverting as little as possible the driver from his main driving task and providing him with sufficient information.

UTILITY OF EYE MOVEMENT RECORDING IN SPATIAL ORGANIZATION OF A DASH BOARD

The driving task requires a continuous stream of decisions based 90 % on visually acquired information (lane and speed control, anticipation of the trajectory and of the effects of manoeuvres, adaptation to the traffic and the environment...).

Various sorts of external visual informations are acquired during actual driving (see : Michaels and Cozan, 1963 ; Gordon, 1965, 1966 ; Bhise and Rockwell, 1971 ; Robinson, Erikson, Clark, 1972...). The traditional approach of roadway engineers to modify driver performance and prevent accidents is to improve road conditions (traffic signs, road markings and delineation...), but this is of little help for the design of instrument panels.

Other factors, probably very important in driving safety, are the individual factors, like : cognitive load of the drivers, subjective risk evaluation, state of drowsiness... (see : Michaut, 1968 ; Pin, Lecret, Pottier, 1969 ; Matthews and Cousins, 1980 ; Neboit, Laya, Hella, 1983). But seeking to modify driver behaviour by inducing an attitude change is not of the resort of an automobile manufacturer.

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The important criteria in the design of instrument panel are relative to the car interior such as :

- positioning of the information source,
- legibility, graphic form or semantic content of messages,
- match between the way in which information is presented and the sensory capacities of the person receiving such information,
- etc...

For example, it is frequently seen in the literature, that the analysis of an operator's eye movements can contribute to the spatial organization and distribution of information in the working environment (White, Warrick, Grether, 1953 ; Lincoln and Averbach, 1959 ; Williams, 1966 ; Dubois-Poulsen, 1977 ; Spérandio, Bouju, 1983).

In the "Laboratoire de Physiologie Renault", we conducted an experiment to investigate the time needed for the eye to move from a target outside a stationary vehicle, to explore one of six positions of a display in the car, and to return to the original fixation point, distant 7 m from the driver. We collected eye movements of ten subjects wearing a NAC eye-marker camera and who where instructed to read aloud a number on the display ten times.

It seems that as the angular eccentricity of the display increases, the proportion of time that cannot be used for the acquisition of visual information increases (see Figure 1).

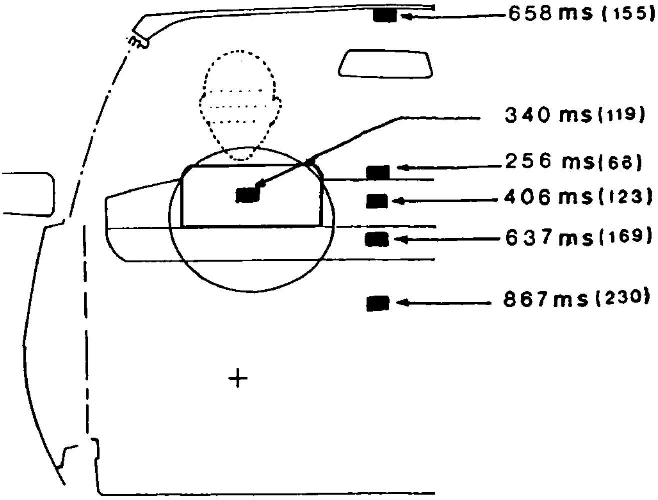

Figure 1
Average durations of eye movements (in ms)
and scatter for each location (10 subjects)

It is important to establich such a weighting for each position of the dashboard, but this is not sufficient for an ergonomic arrangement of the instrument panel because we cannot quantify the respective influence of each zone or instrument as a function of particular phases of the driving task.

ANALYSIS OF VISUAL TIME SHARING IN DRIVING

It is obvious that we need quantitative studies of the effect of automobile displays on the ability of the driver to acquire external visual information in actual driving, but recording eye movements in a natural situation of driving raised additional problems of those normally met in the laboratory. A "natural" setting is a very complex environment where the different independent variables are not controlled and the subject's responses not limited. The complexity of the driving situation can render unrealistic a simple interpretation of the sources of information observed by the subject.

For these reasons, we chose to investigate the inverse question, namely : the influence of the perceptual demands of different situations on the maximum duration of consultation of a display on the dashboard (Hella, Rebiffé, Hartemann, Le Breton, 1983).

In three different actual driving situations (three levels of the primary task) we recorded eye movements of ten drivers by use of the electro-oculographic method (which only measures relative displacements and not absolute position of the eyes in the visual field). The secondary task consisted of reading several times and as many as possible of the numbers passing accross a liquid crystal display fixed on the middle of the dashboard. At this stage, we assumed that mean consultation times on the dashboard are related to the perceptual load of the driving situations.

Results in Table 1 show a decrease in the mean consultation times as the traffic flow increases.

Major National Road :	1.92 seconds
Expressway :	1.67 seconds
Urban Road :	1.42 seconds

Table 1
Mean consultation times in relation to driving situation (averages for 10 subjects)

Interindividual differences are very large : some drivers distracting their eyes for only 1.5 seconds whilst others accept durations of 4 seconds (see Table 2).

Maximum duration of visual distraction

	seconds :	1.5	2.0	2.5	3.0	3.5	4.
Driving Situations	Urban road	4	3	3	-	-	-
	Expressway	1	4	2	2	1	-
	Major National Road	1	4	-	2	2	1
		6	11	5	4	3	1

Table 2
Distribution of 10 subjects as a function of the maximum duration of consultation in 3 driving situations

Major conclusions are as follows :

- As the attentional and perceptual demand of the driving task increases, the time allocated to the consultation of dashboard instrumentation decreases. These data suggest a limitation of the amount and the complexity of information to be delivered to the driver.
- There are considerable individual differences among subjects, probably related to differences in subjective risk evaluation, but we had no means to judge the objective risk incurred by the driver.

LIMITS OF THE USE OF EYE MOVEMENT DATA FOR EVALUATION OF DRIVING PERFORMANCE

This finding raised the same question as previously : how to judge the effect of consultations inside the vehicle on the risks incurred by the driver during the time his attention was no longer on the external environment ?

At this point, the use of eye movement recording was limited by the difficulties encountered when attempting to infer the mental processes involved in complex environment, such as : impossibility of controlling the information available to the subject and to study its influence on the driving task. This is why we sought to describe driver performance in terms of lane control.

Further research was conducted to investigate if subjects could maintain lane position and direction while performing a secondary task of acquiring information inside the car.

15 subjects were instructed to read different numbers of digits on a display at different locations inside the vehicle at the same time as they drove on a straight 150 meter lane. This experiment was performed under the following set of conditions :

- Velocity : 55 km/h (controlled by experimenter),
- 5 locations of the display inside the car (see Figure 2),
- 3 consultation times (measured by the number of items read) : 1.3, 3.0 and 5.0 seconds,
- 15 trials per condition.

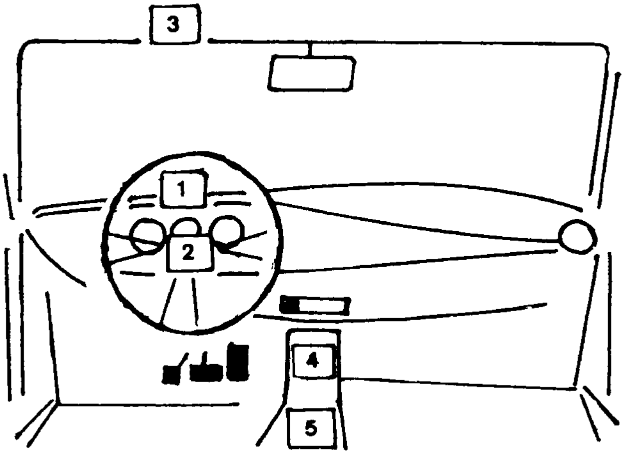

Figure 2
Locations of the display inside the vehicle

Deviations from the trajectory were measured using a device fitted to the rear of the vehicle. Prior to data collection, in this experiment, the subjects were asked to drive on the test section ten times (control performance).

Figure 3 presents the major results of this study.

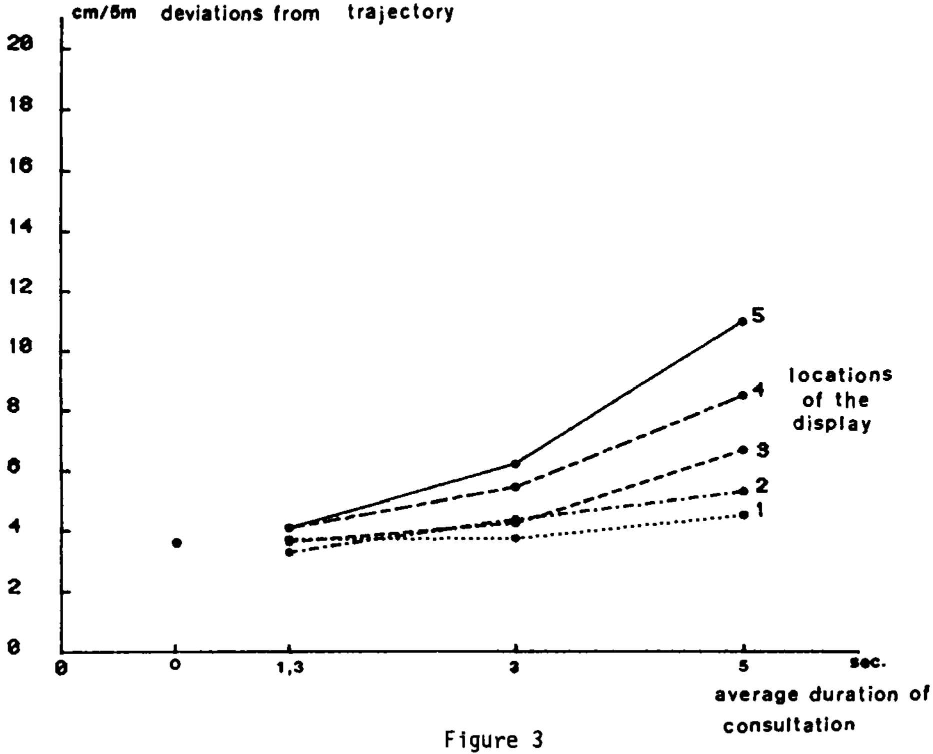

Figure 3
Deviations from trajectory as a function of the position of a numerical display and mean durations of consultation

Data show that the loss of precision in controlling the vehicle is related to both the duration of consultation and the eccentricity of the numerical display.

With increase in angular eccentricity the time available for the consultation of a display inside the vehicle decreases, probably because the reduction of the portion of extra-foveal information necessary for maintaining lane position is larger. These findings suggest a classification of the possible localisations of instruments and displays so as to minimize the objective risk in actual driving.

CONCLUSION

Up to now presentation of information in a car was almost exclusively visual. This is why we were encouraged to use eye movement recording in favour of other techniques for studying information acquisition and processing in vehicles. This set of experiments raised the problem of the interpretation of eye movement data recorded from subjects performing a driving task, for instrument panel design. Interpretation depends essentially on :
- The choice of eye movement parameters appropriate for the analysis of the task.

- The nature of the experimental situation, that is :
  - laboratory,
  - simulation of real environment,
  - or "natural" situation.
- The interaction between the subject, the driving task, and the environment.

The aim of this experimental work was to provide results with some practical implications in automobile instrument panel design.

Analysis of temporal aspects of eye movements was very appropriate to measure the effects of eccentricity of a display on the duration of eye movements and to evaluate the time available for information acquisition as a function of driving situations. But when coupled with other information about driving performance (as lane control) these indices provide a richer set of data for application.

ACKNOWLEDGEMENTS

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

Behavior Oriented Vision: Functional Field of View and Processing Resources

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ABSTRACT

Peripheral vision performance was examined under free eye movement in natural behavior. As the target, a small spot of light was presented spatially and temporally at random in actual driving. The subjects' task was to make detection response orally during driving. The reaction time and the eye movements were measured. It was clearly shown that, with the increase of situational demands, reaction time becomes longer, and response eccentricity becomes shorter. The latter indicates the narrowing of the functional field of view. In addition it was found that these two are negatively correlated. The result was further confirmed in cases when subjects responded without eye movements. Furthermore, it was found that latency of eye movements is larger in more demanding situations. This suggests that processing around each fixation point is deeper. There seems to be a kind of trade-off between depth and width of processing in the functional field of view. It was suggested that the decrease of peripheral vision performance was due to optimization of allocation of processing resource for coping with demands, and necessity of field experimentation was briefly discussed.

INTRODUCTION

The present paper attempts to explore some of the functional aspects of eye movements and peripheral vision performance for the acquisition of information in natural behavior. Eye movements and peripheral vision are essential for our selective acquisition of visual information, that is, for coping with various kinds of demands. Though the whole visual field is about 210 deg wide, the most sensitive area of the retina is only about 2 deg wide. Therefore, we move our eyes to catch informative objects with the sensitive area. It is important where and how we direct the sensitive area (foveal vision). However, we acquire information not only by foveal vision. To direct foveal vision, it is indispensable to get some cue from peripheral vision, otherwise eye movements become random and acquisition of information becomes inefficient. Thus, in a certain sense it can be said that peripheral vision is much more important than foveal vision.

Sanders (1970) classified the visual field according to functional differences. However, the size of the visual field changes with differences in tasks and state of subjects. For example, when the task in foveal vision is difficult, the peripheral visual field becomes narrower (e.g. Leibowitz and Appele, 1969; Ikeda and Takeuchi, 1975; Williams, 1982), and when subjects are anxious, the peripheral visual field becomes narrower (e.g. Weltman and Egstrom, 1966). These and other experiments on peripheral vision were conducted by eliminating eye movements for the ease of experimental control. However, peripheral vision should be examined under free eye movements, since peripheral vision has a significant role in eye movement guidance. One more point is that most experiments on acquisition and processing of visual information are conducted in laboratories. The subjects' own purposeful behavior is not involved. Acquisition and processing of visual information should be be examined in relation to our own behavior. That is, it should be examined in situations where visual information is highly needed for our behavior. Nonetheless, characteristics of peripheral vision with free eye movements in natural behavior have never been examined. By such experimental studies, we could understand more about acquisition and processing of visual information.

AIM OF THE PRESENT STUDY

Since it is one of the most common forms of behavior in which visual information is highly important, driving was investigated in the present study. It is generally said that, in driving, more than ninety percent of available information is visual. In our behavior, especially in driving, the temporal context and the temporal pressure of information acquisition cannot be ignored. So, in examining the acquisition of visual information in a temporal context, gaze duration has significance. In our preceding eye movement study in driving (Miura, 1979; Miura and Nagayama, 1980), it was shown that with the increase of visual tasks, that is, with the increase of situational demands, the mean gaze duration becomes shorter. Why does gaze duration become shorter with the increase of demands? It can be hypothesized that, in situations with larger demand, the size of the peripheral visual field becomes smaller (Miura, 1982a). That is, in order to cope with larger demand, it is necessary to acquire more information with the narrower visual field in a certain time period, so, as a result, gaze duration is shortened.

The present study aimed to test this hypothesis, and to clarify the relation between the necessity of information acquisition and the size of the peripheral visual field under free eye movement conditions in several traffic environments. Under tachistoscopic conditions and fixation conditions, that is, under conditions without eye movements, it is shown that the peripheral visual field becomes narrower with increase of foveal load (e.g. Ikeda and Takeuchi, 1975) and with increase of incentive (e.g. Bahrick, Fitts and Rankin, 1952). Under free eye movement conditions, can the narrowing be found? If it is found, what is the function of changes in peripheral vision performance? What kind of changes can be found in the mode of eye movements? Here, functional aspects of eye movements and the performance of peripheral vision will be focussed on, and some aspects of the underlying mechanism will be discussed.

METHOD

In examining peripheral vision performance under free eye movements, there are many indices. Among them, there are two major indices. One is reaction time, that is, how fast subjects can detect a target appearing in the peripheral visual field, with eye movements. The other is how wide is the region around each fixation point where information can be utilized. This range around each fixation point is called the functional field of view. The following method was developed and applied to examine simultaneously eye movements and peripheral vision performance.

The experiment was conducted in actual driving in daytime. The target was a small spot of light with a luminance of 40 cd/m^2, presented about 55 cm from the subjects on the back of the windshield. A target appeared spatially and temporally at random, and disappeared with the subjects' response. The stimulus field extended to about 40 deg wide and 20 deg high, and the diameter of a target was about 0.5 deg. The subjects' task was to explore scenery farther ahead with free eye movements and to make orally a detection response as soon as possible during driving. The mode of the response reflects the characteristics of peripheral vision performance. The reaction time was measured, and at the same time, eye movements were recorded by an eye camera (NAC model 4) and analysed. Eighteen indices were analysed in each trial. Some of these are shown in Figure 1. All data were video recorded (SONY SLO-350). Analyses were performed by a video disk recorder (Victor VM-1200) frame by frame. One frame corresponds to 16.7 msec.

Reaction time indicates the availability of peripheral vision to eye movements, which can be called the available dynamic field of view. And response eccentricity (distance between a target and a fixation point at the moment of subjects' response) represents the size of the so-called functional field of view.

There were five conditions; 1) control condition (C) - sitting in the driver's seat in a stationary car and exploring farther ahead. 2) low crowded route condition (LCR) - driving on a one way route with low traffic density (with three lanes, at about 60 km/h). 3) moderately crowded route condition (MCR) - driving on a moderately crowded suburban route with center barrier (with three lanes, at about 60 km/h). 4) highly crowded route condition (HCR) - driving on a downtown route with high traffic density including pedestrians, bicycles and motorcycles (with one lane, at about 40 km/h). 5) expressway route condition (EW) - driving on expressways with center barrier (with two lanes, at about 100 km/h), and the

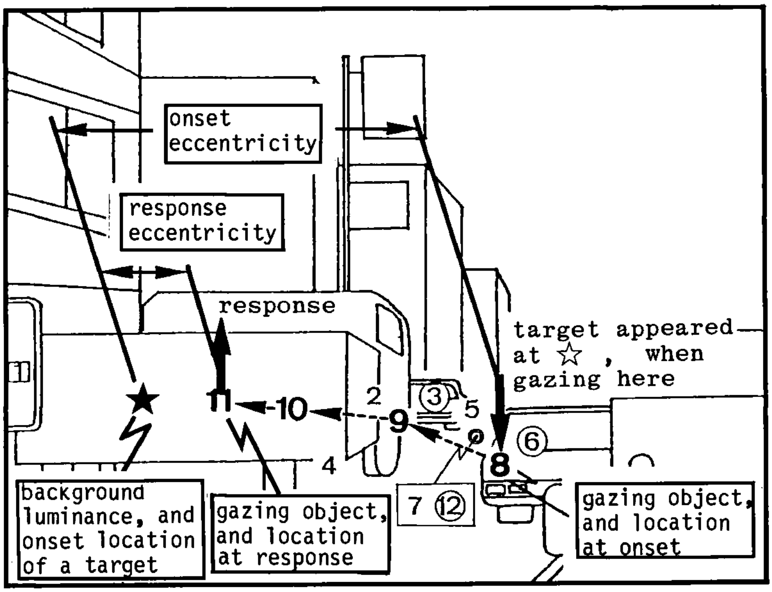

Figure 1. Some examples of indices analysed. Numbers indicate sequence of fixations. When a subject was fixating the point designated by ↓ , target appeared at ★ , and he responded at the fixating point designated by ↑ .

traffic density is between LCR and MCR. Also a fatigue condition on the low crowded route (F) was introduced.

Experiments were performed about 60 times (about one hour a time, during ten months) and about 4500 trials were available for analysis. The mean of onset eccentricity (distance between a target and a fixation point at the moment of target appearance) was 13.6 deg. Background luminance of a target was measured with a luminance meter on the spot in each trial. The mean was about 1200 cd/m^2. Two subjects participated, who were accustomed to driving with the eye camera.

Before the main analyses, a preliminary experiment was performed to obtain data about the relation between the real location of fixation points and location of eye-marks (apparent fixation points as measured by the eye camera). The data were obtained for each subject. Through the results obtained the location of eye-marks was corrected to the real locations.

RESULTS AND DISCUSSION

Before the main examination, at least two factors should be examined. One is the effect of the background luminance on target detection. Contrary to our prediction, no effect was found (Miura, 1982b; 1985c). So, the background luminance is not considered in the main examination. The other factor to examine is degree of demand, that is, complexity of traffic environment in each condition. It is confirmed that there is no difference between the low crowded route and expressway as to the complexity of driving situation, and objects looked at, but that the highly crowded route is much more complicated, that is, more demanding (Miura, 1985a).

Peripheral Vision Performance and Demands

Figure 2 shows reaction time and response eccentricity as a function of situa-

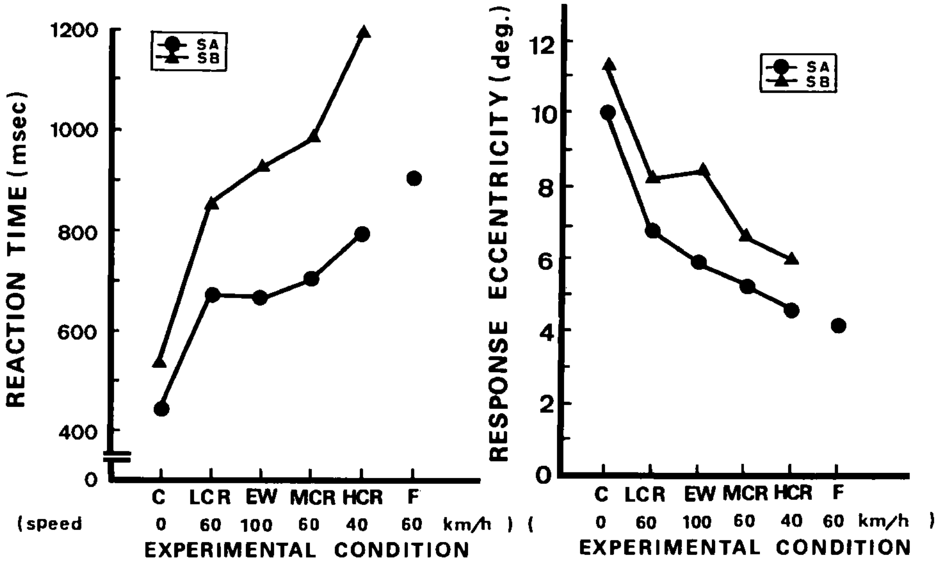

Figure 2. Reaction time and response eccentricity as a function of situational demands. Note. C-control, LCR-low crowded route driving, EW-expressway driving, MCR-moderately crowded route driving, HCR-highly crowded route driving, F-fatigue condition in LCR. SA, SB - subject A, B.

tional demands. It is clearly shown that, with the increase of situational demands, reaction time becomes longer and response eccentricity becomes shorter. Analyses of variance were performed with experimental conditions as a fixed variable and subjects as a random variable. Here, the fatigue condition was not involved. Concerning reaction time, the interaction between experimental conditions and subjects was significant ($F(4,3979)=4.04$, $p<.01$), and the effect of experimental condition was significant ($F(4,4)=9.93$, $p<.05$). Concerning response eccentricity, this interaction was not significant, and the effect of experimental conditions was significant ($F(4,3979)=49.12$, $p<.01$).

Thus, the hypothesis suggested by the preceding eye movement study is confirmed. That is, the performance of peripheral vision decreases with the increase of situational demands. Under more demanding situations, the functional field of view becomes narrower, and delay of awareness with eye movements to peripherally appearing objects becomes larger. This suggests that, in more demanding situations, we may fail or delay to find relevant information, though subjects are trying to acquire more information to cope with the larger demand.

Here, two points should be noticed. Firstly, it is shown that the reaction time and the response eccentricity are negatively correlated. That is, in cases of narrower functional field of view, reaction time is longer. The relation was demonstrated because the present experiment was performed with free eye movements. This is the first finding. Secondly, it is shown that the determinant of the peripheral vision performance is the complexity of the traffic environment, but that as shown in Figure 2, the determinant is not the driving speed itself. That is, more generally speaking, the determinant is temporal density of processing of information, but not temporal density of information input.

These results are based on all of the data in each condition. The mean number of eye movements between appearance of a target and response of subjects was 1.36. These results are further confirmed by the examination of the subset of the data when no eye movements occurred.

Peripheral Vision Performance Without Eye Movements

Figure 3 shows reaction time and response eccentricity when subjects responded without eye movements. This partly corresponds to the common definition of visual field in psychology and medicine. Analyses of variance were performed with the experimental conditions as a fixed variable and subjects as a random variable. As to reaction time, interaction between experimental conditions and subjects was not significant. The effect of experimental conditions was significant ($F(3,1405)==8.92$, $p<.01$). A further analysis of variance was performed to examine the effect of driving conditions, that is, by eliminating the control condition. No significant effect was found. As to response eccentricity, the effect of experimental conditions was significant ($F(3,3)=13.54$, $p<.05$), and the interaction between experimental conditions and subjects was significant ($F(3,1405)=8.16$, $p<.01$).

Here, no difference in reaction times appear among driving conditions. However, response eccentricity becomes shorter with the increase of situational demands. So, it was demonstrated that latency of awareness without eye movements is almost the same among driving conditions, but that the range within which subjects can detect targets without eye movements becomes smaller with the increase of situational demands. This clearly demonstrates the relation between the peripheral vision performance and the necessity of information acquisition.

Latency of Initiating Eye Movement; Decomposing the Reaction Time

Thus far, it was shown that, with the increase of situational demands, functional field of view at each fixation point becomes narrower, and that, with the increase of the demands, reaction time for detecting a target with eye movements becomes longer. Then, what does the length of the reaction time reflect? Here, scan paths were analysed to decompose reaction times. Some examples are shown. (Note that we drive on the left in Japan.)

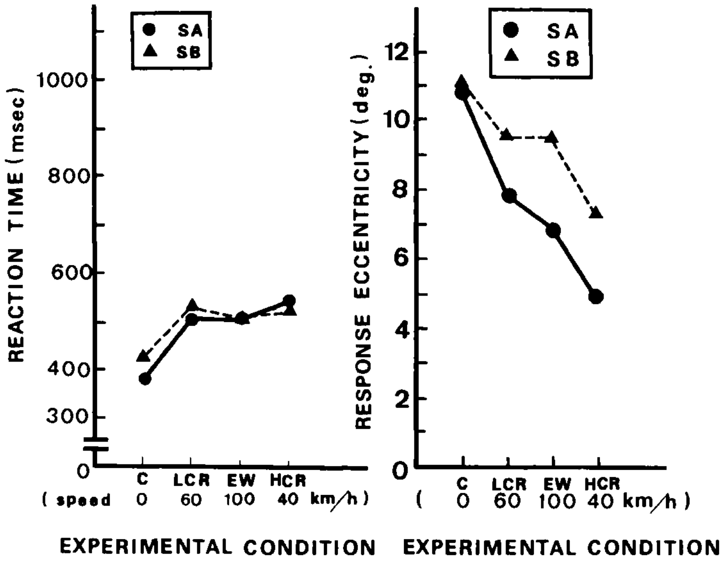

Figure 3. Reaction time and response eccentricity without eye movements as a function of situational demands. Note. C-control, LCR-low crowded route driving, EW-expressway driving, HCR-highly crowded route driving. SA, SB - subject A, B.

Figure 4-a shows a typical scan path under small demand (in stable driving on a low crowded route). In this case, as mentioned above, a subject responded with a short reaction time of 440 msec, without eye movements. That is, he could monitor a preceding car, and at the same time, he could respond to a target appearing in the peripheral visual field without eye movements.

Figure 4-b shows another typical example under small demand (in overtaking on a low crowded route). In this case, a subject responded with one eye movement. But, the reaction time is 440 msec, that is, the same as the former one. Concerning the components of reaction time, latency of initiating eye movement after the appearance of a target is 240 msec, saccadic duration is 50 msec, and latency of response after terminating the eye movement is 150 msec.

On the other hand, Figure 4-c is one of typical scan paths in a more demanding situation (at the beginning of overtaking on an expressway). In this case, the driving situation is similar to the former one, and a subject responded also with one eye movement. But, the reaction time is 1070 msec. The subject seems to pay more attention to the interaction between his own car and the other cars, because of active maneuver in high speed driving. The latency of initiating eye movement is 890 msec, which is much longer than in the former case (240 msec). Saccadic duration is 50 msec, which is the same as in the former case. And the latency of response after terminating the eye movement is 130 msec, which is almost the same as in the former case. So, the longer reaction time is caused by the longer latency of initiating eye movement. This latency seems to indicate the so-called perceptual delay and/or the delay of attention switching to a target appearing in the peripheral visual field.

Figure 4-d shows another typical example in a more demanding situation (at an intersection on a highly crowded route). The situation is more complicated, that is, there are a bicycle and many other cars on a narrower road. Here, a subject responded with one eye movement, with a reaction time of 1280 msec, which is much longer. The latency of eye movement is 690 msec, which is also much longer than in the case of Figure 4-b. Saccadic duration is 70 msec, which is almost the same as in Figure 4-b. The latency of response after terminating the eye movement is

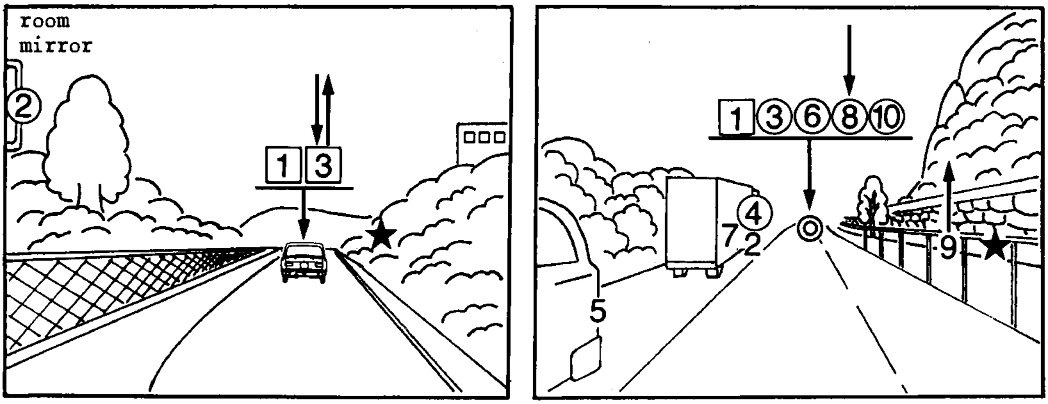

Figure 4-a. A scan path in stable driving on a low crowded route.

Figure 4-b. A scan path in overtaking on a low crowded route.

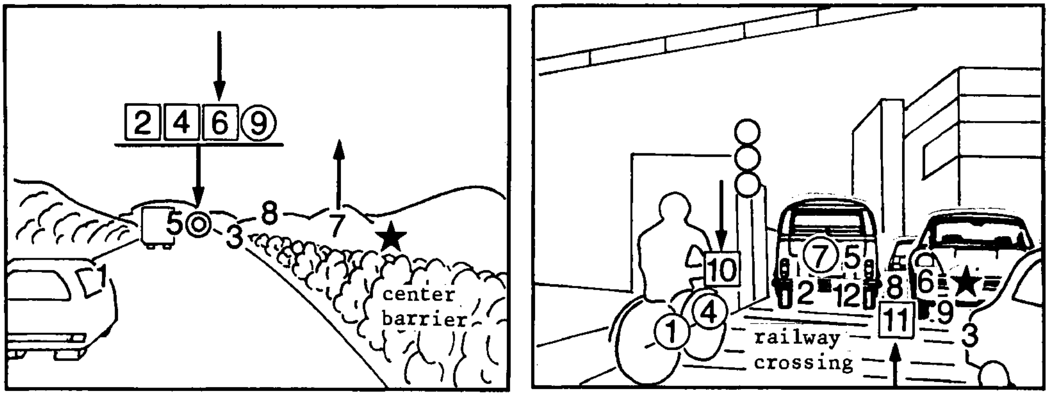

Figure 4-c. A scan path at the beginning of overtaking on an expressway.

Figure 4-d. A scan path in crossing on a highly crowded route.

Figure 4. Typical scanpaths under different situational demands. Numbers indicate sequence of fixations. When a subject was fixating at a point designated by ↓ , a target appeared at ★ , and he made a detection response at a point designated by ↑ . Squares indicate fixations with more than 700 msec duration, circles with between 300 and 700 msec duration, and numbers without marks indicate fixations with less than 300 msec duration. Note that we drive on the left in Japan.

520 msec, which is longer than in Figure 4-b,c. This seems to indicate the so-called response delay. In this case, because of perceptual delay and/or attention switching delay, and response delay, availability of peripheral vision with eye movements is decreased.

Here, the difference in latency of initiating an eye movement after the appearance of a target between less demanding situations and more demanding situations should be noticed. The latency seems to indicate the so-called perceptual delay and/or delay of attention switching to targets which appeared in the peripheral visual field. These delays can be interpreted to indicate the depth of processing of objects fixated.

So, by decomposing the reaction time to peripherally presented targets, it was found that, in more demanding situations, latency of initiating an eye movement after the appearance of a target is larger. This suggests that, with the increase of situational demands, subjects are processing more deeply. That is, in the present experiment, reaction time seems to be able to indicate some aspect of the depth of processing for coping with situational demands.

GENERAL DISCUSSION

Allocation of Resources

Because the present experiment was conducted under free eye movement conditions, peripheral vision performance was examined with several indices at the same time, here, mainly with reaction time and response eccentricity. It was demonstrated that peripheral vision performance decreases with the increase of situational demands. This was further confirmed in cases when subjects responded without eye movements. Furthermore, by decomposing the reaction time, it was suggested that in more demanding situations processing around each fixation point is deeper. Therefore, it is suggested that, in more demanding situations, processing is deeper, but at the same time peripheral vision performance decreases. The deeper processing seems to be one of the causes of both the lengthening of the reaction time and the narrowing of the functional field of view. So, it was shown that reaction time and response eccentricity are negatively correlated. Based on these findings, it is suggested that it is hard to process deeply and widely at the same time. There seems to be a kind of trade-off between depth and width of processing at each fixation point in the acquisition of information. This can be represented schematically in Figure 5.

Then, how do subjects acquire information with the narrower functional field of view in more demanding situations? Miura(1985b;1986b) attempted to examine this point. He estimated the size of the functional field of view both by onset eccentricity (distance between a target and a fixation point at the moment of target appearance) and by the number of eye movements between target appearance and subjects' response, on the assumption that fixation points shift to the margin of preceding functional field of view. The estimated size was compared with the obtained data. It is suggested that in more demanding situations subjects shift

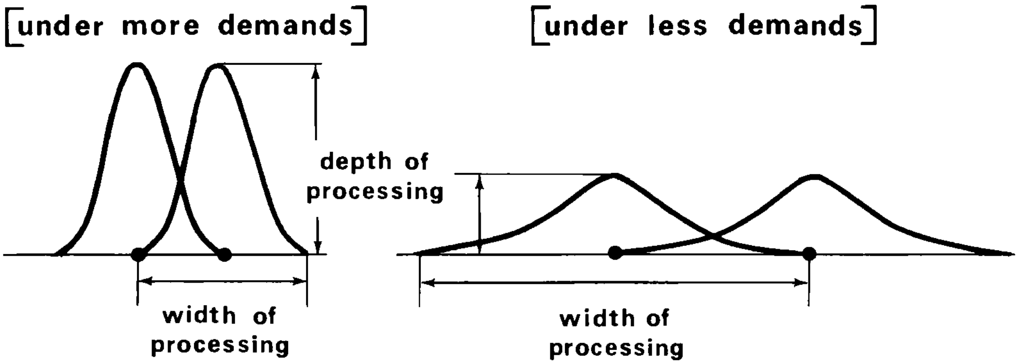

Figure 5. Schematic representation of depth and width of processing in the functional field of view. The dots (●) indicate succeeding fixation points.

fixation points more marginally, that is, fixation points move close to or out of the margin of the functional field of view around the preceding fixation points. And, at the same time, it is suggested that the overlapping area of functional field of views around succeeding fixation points decreases. This mode of scanning seems to be efficient for acquisition of information but to run the risk of missing information.

This suggests that, in more demanding situations, the functional field of view becomes narrower because of deeper processing, and that, at the same time, subjects have much more readiness to acquire information in the peripheral visual field. This mode of eye movement exploration (which reflects greater readiness to acquire information), and the narrowing of the functional field of view (which reflects deeper processing at each fixation point), together suggest the optimization of allocation of processing resources for coping with larger demand. The greater readiness for acquisition of information and the deeper processing mentioned above reflect the "COGNITIVE MOMENTUM" (Miura, 1984). The decrease of peripheral vision performance should not be taken merely as a deterioration but as an optimization of acquisition of visual information.

Necessity of Both Field Experimentation and Laboratory Experiments

One further point that should be discussed here is the necessity and the usefulness of field experiments. A difference in gaze duration for coping with demands is found between a field experiment (Miura, 1979) and laboratory experiments (Miura, 1979; Antes and Penland, 1981). With the increase of demands, gaze duration becomes shorter in the field experiment, whereas, it is shown that gaze duration becomes longer in laboratory experiments (Antes and Penland, 1981). The point lies in the difference of temporal pressure on information acquisition between more natural behavior in the field and behavior in laboratories. This corresponds to the finding obtained here that shows that the determinant of the peripheral vision performance is the temporal density of information acquisition and processing. Moreover, it is shown that the peripheral vision performance is determined much more by situational variables than by the objects at which subjects are looking (Miura, 1986a).

This suggests the necessity of examination of temporal context and temporal density of information acquisition. These cannot be ignored for understanding more about our acquisition and processing of visual information. Furthermore, the findings obtained here no doubt correspond to some causes of accidents in demanding situations. More experimentation on natural behavior is needed, while at the same time laboratory experiments are needed for more precise examination under experimental control.

To conclude briefly, a decrease of peripheral vision performance with the increase of situational demands was demonstrated under free eye movement conditions in natural driving behavior. It was suggested that the observed decrement of peripheral vision performance is an optimization for coping with situational demands.

Acknowledgments

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EYE MOVEMENTS: From Physiology to Cognition
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THE COGNITIVE SIDE OF VISUAL SEARCH IN RADIOLOGY

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Search is composed of survey and examination fixations which, when coupled, form basic perceptual-cognitive decision units. These basic perceptual-cognitive units feed the interpretative decision-making process. Search stages depend on the effectiveness of perceptual-cognitive units. The survey or screening aspect of the perceptual-cognitive unit contributes mainly to global and discovery search stages. The examination aspect of the perceptual-cognitive unit contributes mainly to the reflective search stage. Contrast affects the efficiency of the perceptual-cognitive unit by decreasing surveying and screening and shifting the analysis to the examination side of visual search.

INTRODUCTION

This paper presents a model of the visual search behavior of radiologists performing the task of reading chest x-ray images for small circular targets called lung nodules. We have been using eye movements to study this task for a number of years. The task of detecting lung nodules is important from a medical standpoint because these abnormalities often signal the presence of cancer, and early detection is desirable for effective treatment. However, a significant number of lung nodules, 10-30 percent, are missed during routine screening by specialists trained to read medical images.

The primary reason for the high rate of error in searching for lung tumors in chest x-ray images is that these targets are embedded in a structured anatomical background containing ribs, blood vessels, and lung tissue. These anatomical structures often act to either occlude or otherwise camouflage the nodule target. Whether or not a nodule target is detected depends primarily on three factors: training and experience; degree to which the target is occluded by the camouflaging background; and, size, contrast and edge sharpness of the target. High contrast nodules stand out against the anatomical background whereas low contrast nodules blend into the anatomical background. Thus, because the targets are embedded in noisy backgrounds modeling search requires consideration of interpretation and decision-making processes as well as target detection. This means that a "detected" nodule must often be further evaluated by an interpretative process that leads to a decision about whether or not it is a true abnormality in the lung. Consequently, the problem of modeling search becomes more complex.

In the present study, subjects were radiologists. They searched chest x-ray images for lung tumors. Half of the images were normal and half contained a 1 cm nodule of either high or low contrast.

Three questions guided the development of the model. First, How does a global assessment of the image affect search? Second, How do perception and cognition cooperate in search? Third, What roles do peripheral and central vision play in search? These questions form the basis for the present paper.

THE SEARCH MODEL

Search for lung targets is modeled as a serial process that has both perceptual and cognitive components and proceeds in four stages: Global Impression, Discovery Search, Reflective Search and Post-Search Recall. Figure 1 shows the search model.

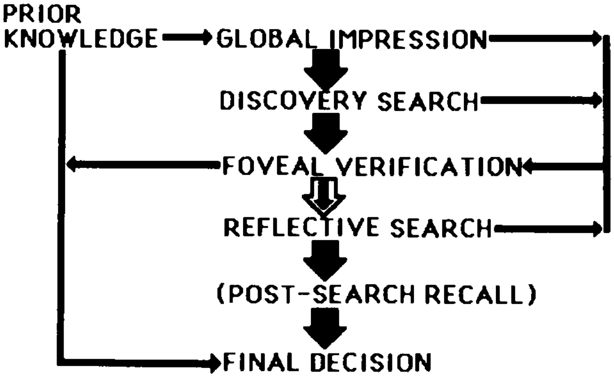


Figure 1. The search model. See text for explanation.

Prior knowledge feeds the Global Impression which, in turn, feeds successive stages of search indicated by heavy dark arrows. The paths to a final decision for Global Impression and Discovery Search are through Foveal Verification. Reflective Search requires extensive Foveal Verification indicated by the heavy double arrow. If a decision is not reached before the display is terminated, Post-Search Recall is called upon.

<u>Global Impression</u>. Peripheral vision plays a dominant role in the global impression providing an overall characterization of the image during an

initial coarse screening by identifying gross departures from the observer's normal prototypic chest. Once these departures from normality are identified, either they can be verified foveally, or, they can be used as input for subsequent stages of search in the sense of specifying a set of potential target features or locations to be fixated and evaluated during discovery or reflective search. If viewing time runs out, they have to be evaluated by post-search recall.

Discovery Search. Primed by the input from the global impression, discovery search consists of sampling the image systematically with the useful visual field to uncover hidden targets. Properties of the target, especially its contrast and edge sharpness, determine the size of the useful visual field (Engel, 1977), and this in turn determines the spacing of successive sampling fixations. As potential targets are discovered, foveal checking can be deferred, or carried out immediately. The model distinguishes between the decisions that result from discovering a target by fixating and evaluating it immediately, and decisions resulting from a more drawn out process of reflecting on a previously fixated, but unresolved target. The objective of discovery search is to apply coarse screening to the image in order to detect potential target features, evaluate them and decide if they are part of a nodule target.

The objective of Reflective Search is to build up enough visual evidence through detailed screening of the image to make a decision about a complicated or ambiguous target.

If search time is limited, as it usually is in laboratory studies, and a decision is not made before the display is terminated, observers are forced to make a decision when the image is no longer visible, by recalling it from memory. This is called Post-Search Recall. When viewing time is unlimited, as is the case in clinical practice, reflective search continues until the observer reaches a definitive decision.

The search model is an elaboration of our previous orientation and scanning model (Kundel & Nodine, 1975; Kundel, Nodine & Carmody, 1978). It is also closely related to a two-stage search procedure proposed by Swennson (1980). The first stage performs an initial screening of the image by means of a preattentive filter which limits the number of image features or potential target sites receiving attention. This is equivalent to our global impression. The preattentive filter mechanism provides input to drive the second stage which consists of attending to potential target features, and explicitly evaluating them either as normal or abnormal. Our model elaborates Swennson's second stage by specifying how attending to target features is related to interpretation and decision making. Any model that addresses search for targets embedded in pictorial images which does not account for how data acquisition by visual scanning is related to cognition is incomplete.

PRIOR KNOWLEDGE, TRAINING AND EXPERIENCE

In order to assess the contributions made by perceptual and cognitive proceess to search, we have developed a random-walk scanning algorithm (Toto, 1985). This algorithm generates a series of saccades and fixations. The sequence of fixation locations is random, but the other properties of the eye-movement pattern such as the fixation-dwell distribution, and the interfixation saccade-length distribution are based on data taken from skilled observers. A decision-making algorithm has not been added yet, but we have plans to do so in the future. The random-walk algorithm provides a picture of what scanning looks like when it is driven without knowledge or perception about the object of search.

Training affects search as reflected in fixation distributions over a chest image generated by the random-walk algorithm, a first-year medical student, and an experienced radiologist. A comparison of random and novice vs. expert shows that the radiologist's fixation distribution is more systematic and covers more of the relevant target area, about 60 percent of the lungs, which may contain the object of search, a nodule target. Coverage is not exhaustive. This is because the radiologist draws upon knowledge and experience to focus search on likely nodule sites.

The importance of prior knowledge in focusing search on potential target sites is illustrated in Figure 2.

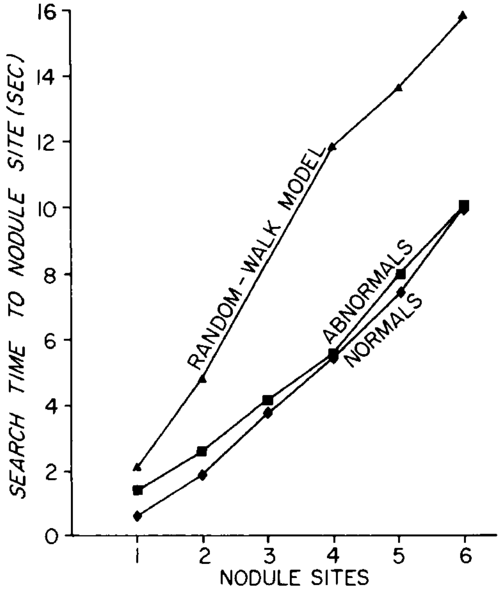


Figure 2. Mean search times to six nodule sites, random walk vs. radiologists searching normal and abormal images.

Figure 2 compares the time required to hit each of six nodule sites using the random-walk algorithm (top curve) against experienced radiologists. Nodule sites indicate actual nodule locations on abnormal (eg. nodule containing) images, and potential nodule locations on normal images that are nodule free. The mean rate of hitting nodule sites (within + 2.5 deg.), which is approximately linear with time, is 30 percent slower for randomly-generated fixations (3 sec. search per nodule site) than human observers (2 sec. search per nodule site). More striking are the data showing the percentage of nodule sites hit which is shown in Figure 3.

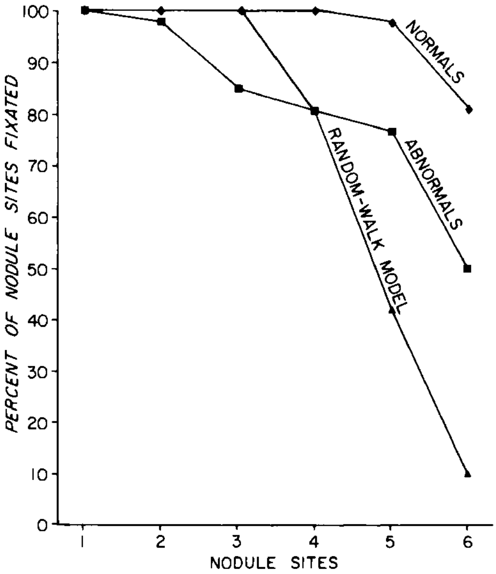


Figure 3. Mean percent of nodule sites fixated, random-walk vs. radiologists.

Note the dramatic fall off in performance after three sites are hit by random-walk algorithm compared to radiologists searching normals. The fall off for real observers looking at abnormals is due to detection of nodules which terminates search early. The difference between the random-walk curve and the two human-observer curves show how much perception and cognition contribute to search. That nodule sites are hit by radiologists with high regularity on abnormal images is not surprising, but that they are also hit on normal images is. This provides evidence that search is driven, at least partly, by cognitive factors like training and experience. In the case of normal images, radiologists searched areas which had previously been shown to contain nodule targets. Because the data was taken on normal images, these areas do not contain nodules. Rather, they contain normal features and so have no inherent attractiveness from a perceptual standpoint.

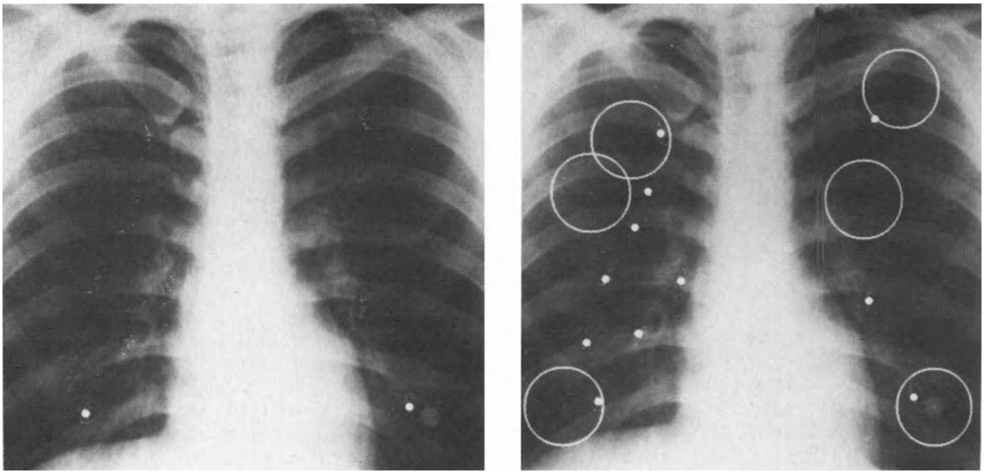
Searching for targets in images containing pictures of anatomy is quite different than looking at pictures containing shapes, lines and colors, as this final comparison between radiologists searching x-ray images for nodule targets and subjects examining abstract paintings indicates. First, fixation dwells are longer for search (Mean = 360 msec.) than examination (Mean = 280 mec., $t\ (3495) = 11.43$, $p < .01$). Second, saccades are shorter for search (Mean = 4.43 deg.) than examination (Mean = 4.72 deg., $t\ (3495) = 2.10$, $p < .05$). This suggests that search tasks require more comprehensive coverage of the image, in the sense that sampling is more selectively dense on pictorial detail, than that required to make a judgment about an artwork (Locher & Nodine, this volume).

RELATIONSHIPS BETWEEN THE MODEL AND SKILLED SEARCH

The data that we have presented so far indicates that skilled search is systematic, sampling is selective and coverage of potential target areas is comprehensive. Furthermore, skilled search relies upon cognitive guidance when observers have been given experience with search tasks.

One goal of the search model is the identification of eye-movement parameters that are related to successful search where successful means deciding that an image contains a nodule target when it does (true positive), and deciding that an image does not contain a nodule when it doesn't (true negative). We view each fixation as a potential decision node. However, we distinguish between survey fixations which function to provide the observer with an overview, or gist, of the displayed image, and examination fixations which function to gather detailed evidence designed to evaluate or verify a survey impression. This distinction between survey and examination fixations comes from picture-viewing research (eg. Buswell, 1935; Nodine, Carmody & Kundel, 1978). Characteristically, survey fixations have a short dwell (100-200 msec. based on nodule-search data), and examination fixations have a long dwell (> 600 msec. also based on nodule search data).

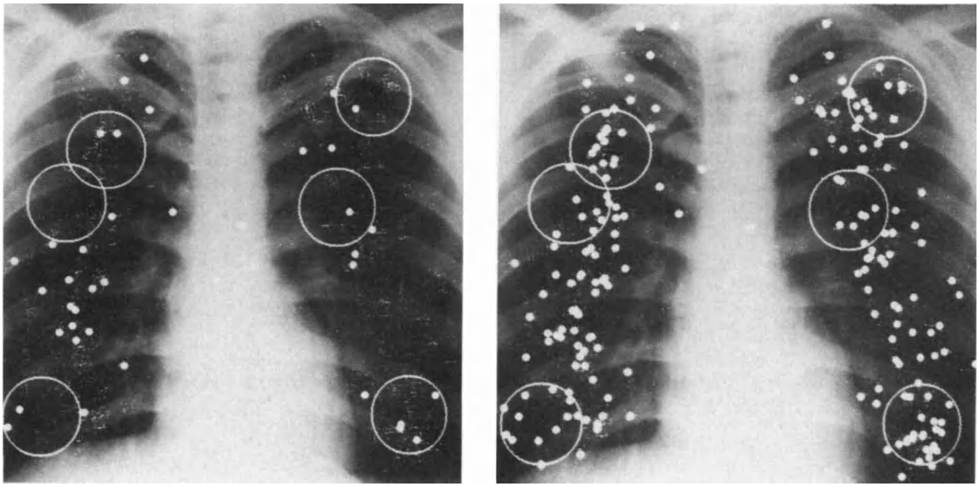
Rather than consider all fixations as potential decision nodes, we have used the distinction between survey and examination fixations as a way of linking interpretative-evaluative decisions to examination fixations as distinct from the primarily perceptual-overview information that results from survey fixations. Thus, using the eye-movement parameter dwell time, we can identify those areas of the displayed image that receive long-dwell examination fixations indicative of evaluative decision making. An example is shown in Figure 4.



Figures 4 and 5. Nodule-containing chest x-ray images showing long-dwell (> 600 msec) examination fixations (left) and short-dwell (100-200 msec) survey fixations (right) for a single radiologist.

All long-dwell (>600 msec.) fixations (there are just two) on an abnormal image are indicated by white dots. The fixation in the patient's right lung is the initial fixation, and the fixation in the patient's left lung which hits within 1.5 deg. of the nodule target is the terminal fixation. Figure 5 shows all short-dwell survey fixations (100-200 msec). Both lungs received a coarse perceptual screening prior to hitting the abnormality. Only 3 of the 12 (.25) survey fixations came within + 1.5 deg. of the six nodule sites, indicated by circles, but the last survey fixation hit the true nodule site, which was followed up by a long-dwell examination fixation as we have already seen in Figure 4. We believe this sequence of alternating between globally surveying the image and following up with in-depth examination of distinctive anatomical detail characterizes a fundamental perceptual-cognitive strategy behind skilled search.

Figures 6 and 7 illustrate the generality of this basic perceptual-cognitive strategy for a random sample of five radiologists searching normal images for lung nodules. Perception and cognition can not be separated because they work together.



Figures 6 and 7. Nodule-containing chest x-ray images showing long-dwell (> 600 msec) examination fixations (left) and short-dwell (100-200 msec) survey fixations for five radiologists.

Figure 6 shows long-dwell examination fixations and Figure 7 shows short-dwell survey fixations. The six 3 deg. circles indicate nodule sites. The interesting point of this comparison is that 42 percent of examination fixations fell on nodule sites, whereas only 25 percent of survey fixations fell on nodules sites. This suggests not only that radiologists regularly deploy a perceptual-cognitive search strategy, but also that the interplay between survey and examination fixations provides insights about the way perception and cognition cooperate during search.

Survey and examination are not separate phases as Buswell (1935) suggested long ago. Rather, they work together as integrated perceptual-cognitive units. These units represent fundamental decision nodes in search. They are identified primarily by long-dwell fixations. The search model builds on this idea in defining the various search stages as we will see next. We now turn to the model which presents a descriptive account of how perception and cognition cooperate during search.

USING THE SEARCH MODEL TO ANALYZE PERFORMANCE DIFFERENCES

The four stages of search can be differentiated by two eye-movement parameters: time to fixate a target; and, dwell time on the target. When the nodule is fixated within 1 sec. of the onset of viewing and reported within another second, we attribute the detection to a perceptual-cognitive process that depends on a global impression. Most nodules are not detected globally but are discovered during subsequent search. Discovery search begins 1 to 2 sec. after the onset of viewing. During discovery search a target is fixated followed by a long dwell, and a decision is made on the basis of the data acquired by this survey-examination unit. Reflective search deals with decisions that are postponed due to a lack of follow-up long-dwell examination fixations after potential targets are surveyed. Ultimately, a potential target site is re-fixated, once or perhaps several times, possibly by comparison scans (Carmody, Nodine & Kundel, 1981), and on the basis of much fixation data a decision is made whether or not to report a nodule. Finally, a target is sometimes fixated and re-fixated during scanning but the decision is postponed until time runs out and the image is turned off. Since the experiment requires a decision, it must be made on the basis of post-search recall.

The model assumes that peripheral guidance is driven by distinctive features that are of sufficient contrast to be detected peripherally. Cognitive guidance is driven by a memory map of previous nodule locations and clinical knowledge of likely nodule sites in the lungs.

Table 1 shows the proportion of true positives associated with each stage of search for high and low contrast nodule targets.

Table 1
Proportion of True Positive Decisions

	Nodule Contrast	
Stage of Search	High	Low
Global	.17	.03
Discovery	.17	.00
Reflective	.33	.33
Post-Search Recall	.02	.14
Totals	.69	.50

As predicted for global and discovery stages, more true positives were found in images containing high-contrast nodules than low-contrast nodules. The visually conspicuous nodule targets are discovered primarily by detecting distinctive nodule features perceptually. When these nodule features are not conspicuous, the yield by perceptual survey decreases, and emphasis shifts from visual to cognitive analysis. Rather than searching for distinctive nodule features, subjects draw on training and experience and focus their search on potential nodule sites in an effort to disembed camouflaged nodule targets.

These findings suggest a qualitative shift in search strategy, from screening the relevant target area for distinctive nodule features to searching known target sites for nodule features. The focus of search has been narrowed down to feature detail within a small area defined as a potential nodule site on the basis of past experience. Carmody and Toto (1985) have shown that decision making accuracy can be significantly increased by pointing attention to potential nodule sites. In our case, the issue is not decoding suspected target areas, but locating targets. The process of disembedding targets as described in the definition of reflective search draws on more detailed pattern analysis and comparison. As Table 1 indicates, almost all low-contrast true positives were found during reflective search, whereas for high-contrast true positives there was a 50-50 split between global-discovery search and reflective search.

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Footnote

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

VISUAL AND PROCEDURAL STRATEGY IN LETTER SORTING USING A VIDEO CODING SYSTEM

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SUMMARY

This study concerns the analysis of a real letter video coding situation. Work pressures were assessed over a sample of ten experienced operators. Certain behavioural and physiological indices appeared pertinent with respect to visual and general work stress. An analysis of visual strategies combined with comments made by the operators enabled us to identify the information processing methods used. The visual strategies employed appear effectively as "operating" strategies.

INTRODUCTION

Over the last ten years, the computerisation of letter sorting has seen important developments in the field of automatic recognition of postal codes. Present technology has not however as yet produced any system capable of identifying addresses with sufficient accuracy independently of the type of writing and their position on the envelope. As a result, human intervention remains an important element in the processing chain. In order to overcome recognition faults, automatic reading systems are backed up by a video coding system. This equipment displays the non recognised address automatically on a screen ; an operator known as an indexer types in the five digits of the postal code. This acquisition enables the system to continue processing the letter (placing an indexing mark, sorting etc.). Human intervention occurs without the letter physically leaving the sorting machine.

The operator's task in video coding consists in locating and identifyng the postal code on the address displayed on the screen and typing in this postal code on a 47-key keyboard (figure 1). The typing process concerns mainly the middle row (keys 0 to 9) ; the top row (keys 0 to 9) is used for 0 complementing the postal code. Thus to index 30346, the five digits are typed in on the middle row. Only two keys need to be pressed to index 45000 however : key 4 in the middle row and key 5 in the top row ; the system automatically generates a five digit 0 complement. The next letter appears on the screen as soon as the postal code has been typed. Corrections are then no longer possible. The duration of the cycle which is of the order of 1-1.5 sec, is determined by the coder typing rate.

The study described below was carried out at the request of the Central Department for Mail Processing. This request followed enquiries from trade union organisations and concerned the consequences for the work force of the use of this video coding system over several hours.

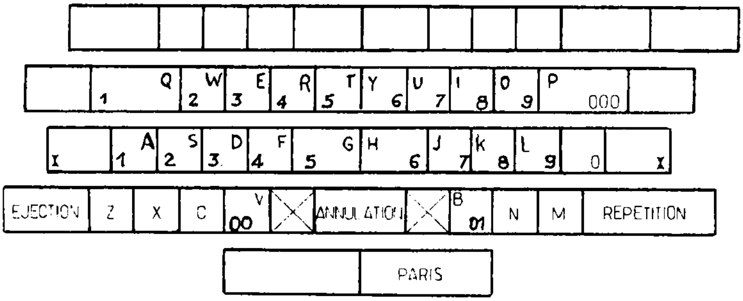

Figure 1 - Coding keyboard

METHOD

At the sorting centre, 10 sorters experienced with the system and all volunteers took part in the study. These 10 operators were monitored over a period of three months, each day from 14.00 hours to 17.00 hours, in 3 periods of 50 minutes followed by 10 minutes rest.

Before starting this study, the video coding room was completely reorganised and indirect lighting installed in order to produce a satisfactory balance of brightness in the visual field of the operator and to eliminate screen glare. None of these elements can therefore be quoted as a source of visual constraint.

Similarly, a clinical and medical examination and a complete opthalmological examination of all operators were carried out with the aim of detecting any previous history or present complaint which might influence results.

As for the study proper, we attempted on the one hand to assess the work load by means of a comparative analysis of physiological and behavioural indices using operators working alternately on SIVIC (video coding system) and PIM (manual indexing station) and on the other hand, we tried to evaluate the difficulties encountered by the operators in performing the indexing task.

1. ASSESSMENT OF WORK LOAD

Assessment of the work load took into account all the various component items of the task which might have an effect on the psychophysiological state of the operator.

The experimental protocol was as follows :

- A questionnaire concerning the main factors of annoyance was completed by seven operators.
- Six self-assessment scales (arousal and stress states) were applied before work started at the end of the 1st, 2nd and 3rd hours to 9 subjects working on PIM and SIVIC. These operators completed a mini-questionnaire under the same conditions concerning the stress symptoms.
- 4 functional tests (measurement of phoria, measurement of the punctum proximum of accommodation, reaction times to visual and auditory stimuli) were given to the same operators.
- Continuous observations were made during work on SIVIC and PIM in order to differentiate between encoding periods proper and waiting periods.
- Continuous recording of heartbeats (FC) during work on PIM and SIVIC in the case of four subjects).

The heartbeat recordings were used to calculate the average heartbeat rate and its variability (sinus arythmia) for different work periods depending on the activity of the subjects.

2. DIFFICULTIES INVOLVED IN EXECUTION OF THE TASK.

This second part of the study aimed to evaluate the difficulties encountered by operators in carrying out the task. The main difficulty seemed to reside in the process of identification of the postal code ; added to the variability of address configuration (handwritten or typed), there was variability in the location of the address on the screen. In fact, the present design of the video coding system does not enable us to precisely locate the letter on the screen. Display is random and the image may be truncated. Finally, the principle of image creation by digitization produces alterations in the characters displayed.

In order to understand the difficulties encountered by operators in the search and identification of the postal code, we used a complementary recording of visual strategies with a NAC EYE MARKER RECORDER (NAC) and verbalisation of the reasons for the choices made by the operators.

Recording of visual strategies was carried out in an actual work situation on SIVIC with 9 operators. We recorded twenty minutes of visual activity for each subject and examined 5 minutes chosen from between the 5th and the 15th minute.

A great many experiments concerning analysis of eye movements have demonstrated that in an actual work situation the direction of visual attention was neither random nor focussed onto priority areas, but that operators chose to look only at information which seemed to them to be useful and in those places where the probability of its appearance was greatest (Sperandio and Bouju 1978).

It seemed probable to us that the visual strategies adopted by operators during indexing procedures would depend on the type of letters to be indexed (handwritten, typed) and the final status given to the letter (indexed or ejected). Visual strategies were therefore analysed in accordance with these parameters.

The relative lack of comments made by operators in the work situation led us to install a medium designed to facilitate verbalisation. A video film made of a representative batch of mail taking into account all cases of distorsion likely to appear in the work situation (i.e. transition from a perfectly legible picture of a letter to an illegible picture) was presented individually to 9 operators for about thirty minutes. They were told to indicate the decision they would make for each letter (indexation ou ejection) and the reason for their choice.

What we were trying to achieve with these two protocols to understand the mechanisms of information processing involved in the letter sorting task.

RESULTS

The phoria measurements made both before work commenced and after each rest period showed no significant differences between PIM ou SIVIC.

The punctum proximum of accommodation showed a significant removal after one hour of work on PIM and on SIVIC (figure 2).

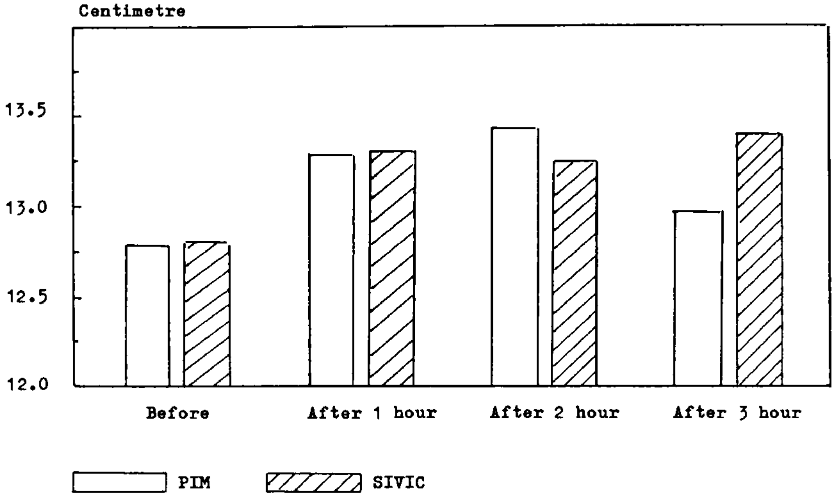

Figure 2. Measurement of the punctum proximum on PIM and on SIVIC.

The reaction times to visual stimuli show no significant difference between the start of the 3 work periods whether on PIM or SIVIC.

We did however notice a significant lengthening of reaction time to auditory stimuli at the end of work on SIVIC. The difference was not significant on PIM (figure 3).

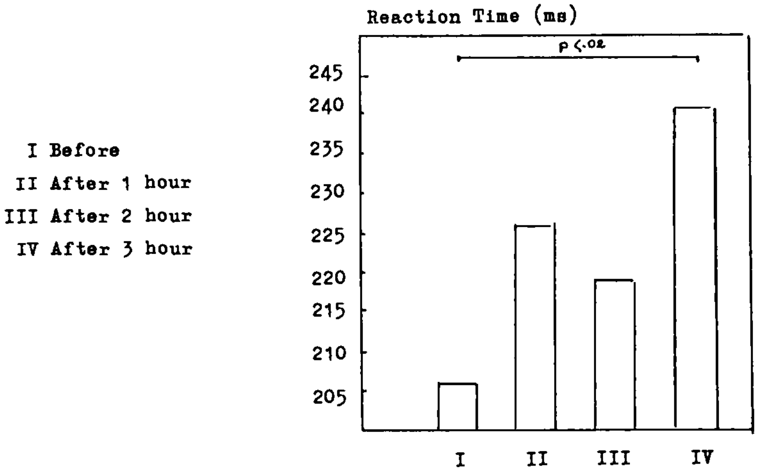

Figure 3. Measurement of reaction times to auditory stimuli on SIVIC.

The results from the self-assessment questionnaires indicate both that arousal declined and that the feelings of stress increased more over the 3 hour test period with SIVIC than with PIM.

The observation of behaviour during work on SIVIC showed an increase in ancillary movements (movements not directly related to the task) from the start to the end of the work session.

1st period : 0.91 movements/5 min.
2nd period : 1.27 movements/5 min.
3rd period : 2.39 movements/5 min.

The average heartbeat was lower in the 3rd period of work than in the first for all subjects working on SIVIC. The slower heartbeat was evident both during typing and waiting periods. Sinus arythmia increased steadily over 3 working periods. This increase concerned both periods of typing and waiting periods. We also noted that within each period sinus arythmia fell off during coding work compared to waiting periods. The difference between the averages (work/waiting) is significant (P .01) (c.f. figure 4).

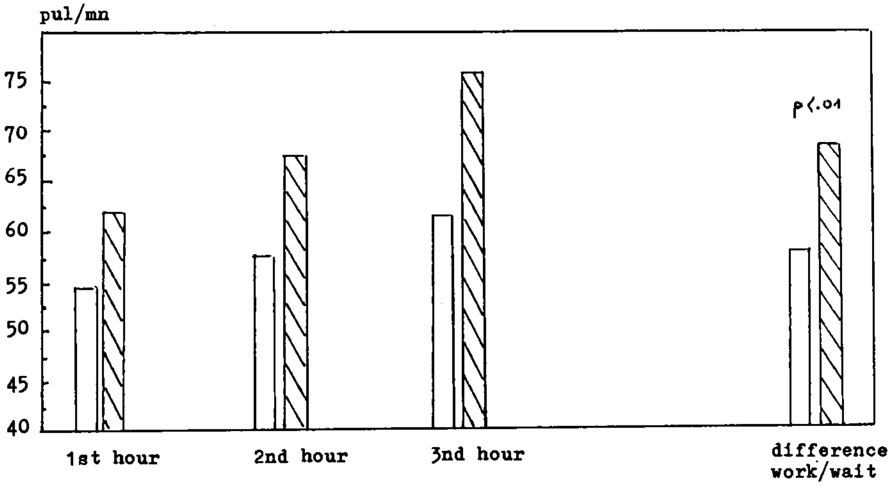

Figure 4. Changes in arythmia on SIVIC.

It emerged clearly from the questionnaire that the predominant annoyance factors for operators were :

- on SIVIC, the lack of focus of the images and the random appearance of addresses,
- on PIM the noise and the mechanical feeding of envelopes.

In addition, many more symptoms of work strain were noted on SIVIC than on PIM and these mainly concerned the operator's vision.

The results of recordings of visual strategies were analysed over a sample of 1563 letters divided into :

734 handwritten letters
692 typed letters
137 non-decodable letters (illegible on the screen or backs of envelopes).
This sample is representative of the composition of daily traffic (50% handwritten letters, 50% typed letters).

Of the 734 handwritten letters, 696 were indexed i.e. a percentage of 94.82% and for the 692 typed letters, 626 were indexed, i.e. a percentage of 90.46%. The indexing percentage was therefore relatively high and shows that the indexing rate is comparable regardless of the type of letter.

The average inspection time taken to index a letter was 1.64 sec. This time allows for system anomalies (no letter presented, presentation of illegible letters, backs of envelopes, momentary breaks in the system).

Analysis of the positions fixating during the task :

Four points appear to be given special attention by the operators. These are in decreasing order of importance :
- the postal code,
- the operator's attention remaining on the spot occupied by the postal code of the previous letter,
- operator's attention remaining on the centre of the screen,
- name of the town.

This order of priority is confirmed both by the number fixations and the total inspection time.

Eye movement recordings were made for 1563 letters giving a total of 3956 fixations over all the operators. The average number of fixations per letter was 2.53.

The principal points inspected were :
- postal code : 38.73%
- spot occupied by previous code : 27.76%
- centre of screen : 14.18%
- town name : 9.61%

For each letter, the operator's visual strategy will therefore be mainly composed of:

- waiting for the letter, either at the spot occupied by the previous postal code (2 out of every 3 letters) or in the centre of the screen (1 out of every 3 letters)
- reading the code,
- where applicable, reading the town name (1 letter in 4).

Using these results, we can therefore see that operators develop a very simplified ocular strategy for indexing which consists in waiting for the appearance of the next letter while attempting to minimise the search for the location of the new postal code :

- The operator focusses his attention on the spot occupied by the postal code on the previous letter (which corresponds to the position of highest probability for the postal code). This tendency is particularly marked in the two fastest subjects who have a speed of between 1.23 and 1.37 sec per letter, as opposed to 2.81 sec for the slowest subject.
- The operator focusses his attention in the centre of the screen, which is the most "strategic" point to minimise eye movement.
- The operator looks at the postal code for indexation and, where appropriate, the name of the town.

Influence of type of letter :

As far as visual strategies are concerned, there was no significant difference between handwritten and typed letters. This economic information retrieval strategy is applied to all letters provided they are visible.
In the case of illegible or inverted letters, inspection times per letter were very short (0,85 sec), the letter was immediately ejected and the operator went on to the next one.

Where there was a gap in the presentation of letters, the subjects explored the screen a little more, looking at areas where the indication of a letter might appear ; this was incidentally the only case in which the screen was explored in a fairly systematic way, but average inspection times in such cases remained relatively short (0,91 sec).

Influence of letter status :

For those letters indexed (1322 letters), the same points were inspected :
- the postal code (68% of time, 41% of fixations),
- waiting time :
  - . either in the spot occupied by the previous postal code,
  - . or in the centre of the screen,
- the name of the town.

Operators fixated on average 2.64 times on each letter which can be broken down into :
- postal code : 1.1
- wait/previous postal code : 0.73
- wait/centre of the screen : 0.36
- town : 0.23

We can therefore see that when indexing a letter, the operator fixated on the postal code and on a waiting area.

In the case of ejected letters, the average number of fixations per letter is lower (1.55), and the wait is more or less the same ; however, the postal code is given proportionally less attention (0.31).

Fixation cycles :

If we analyse focussing cycles per letter, i.e. the order in which information is looked for, we note 190 different cycles. However, they are not all used as frequently as each other. The most frequently used cycles are those which include two fixations : one waiting for the arrival of the next letter and the other reading the postal code.
Examples of fixation cycles and their frequency of occurrence are given in figure 6.

WAIT/PREVIOUS POSTAL CODE	1		1	1			1
WAIT/CENTRE OF SCRENN		1			1	1	
POSTAL CODE	2	2	2	2	2	3	3
TOWN			3		3	2	2
ADDRESS				3			
FREQUENCY	721	170	170	22	80	12	43

1 = in the first place 2 = in the second place 3 = in the third

Figure 6 : fixation cycles during letter indexation.

The town is mainly read after the postal code and this could be explained by the operator wishing to check the coherence of the code.

Finally, insofar as concerns the operator's comments on their activities, the main results are as follows :

9/9 said that they used the town when in doubt as to the postal code.
9/9 said that they knew and had memorised the postal codes for major towns commonly encountered.
3/9 mentioned associative memorising of the code/town pairing.
8/9 did not index letters where doubt remained as to the code/town coherence.
7/9 looked at the whole of the address when the letter is sent to an address near the operator's home town.
4/9 thought that fatigue affected their behaviour. In case of doubt they no longer attempted to crosscheck the postal code by looking at the town but preferred to eject the letter.
8/9 were unable to remember the instructions given to them during training.
3/9 preferred handwritten letters which they saw as more legible.
3/9 preferred typewritten letters as random image display was less common.
2/9 preferred to code the mail using the name of the town when the batch of mail concerned the postal area in which the sorting centre was located.

DISCUSSION

The results obtained from this assessment of work load indicate two types of pressure : visual pressure and general stress feelings.

1. VISUAL STRAIN

The task of video coding makes considerable demands on the operator's vision : prolonged inspection in a limited visual field with minimum variations of depth of focus. This requires the permanently static accommodative effort on the part of the ciliary muscle. The change in position of the punctum proximum of accommodation which occurs after the first hour's work indicates that the operators could be suffering from some visual stress.

The observations made at the work station and the information given by the questionnaire show out-of-focus characters and lack of image location to be among the factors of annoyance. The symptoms of visual annoyance are more frequent on the video coding system than on indexing equipment not fitted with screens (PIM). It is important to stress that the location and lighting of work stations were satisfactory and cannot be put forward as a source of visual pressure (Cail, Elias and Floru, 1984).

2. GENERAL STRESS FEELINGS

The task of video coding requires a high level of attention, short and repetitive work cycles and a steady rate. The information obtained on the self-assessment scales show important differences between the start and the various periods of work. These differences are characterised by a gradual deterioration (fall-off in concentration, feeling of fatigue, drowsiness) and by feelings of stress (tenseness, irritation, anxiety). The deactivation process also results in an increase in auditory reaction times from the start to the end of the work session.

The increase in ancillary movements during the activity complete this picture ; this phenomenon indicates a self-activation effort necessary to maintain attention and probably a behavioural reaction to the uncomfortable feeling caused by the monotony and immobility required by the task.

Heartbeat showed a tendency to fall from start to end of the work. This tendency was true both for work periods proper (coding) and for waiting periods. Moreover, the reduction in heartbeat was not accompanied by any fall-off in performance.

Insofar as the variability of heartbeat (sinus arythmia) of operators working on video coding is concerned, the work/waiting time differences suggest that the lower rate of sinus arythmia during typing corresponds to a stress linked to the effort of concentration. It may equally be assumed that waiting times do not produce the emotional tension normally experienced by operators carrying out dialogue task with a computer.

3. VISUAL STRATEGIES AND OPERATING STRATEGIES

The results of analysis of the NAC recordings and operator comments show that all operators have routine information acquisition strategies. Operators only absorb relevant information.

There is no routine scanning of the whole of the screen before the letter appears neither is there any routine scanning of the whole of the address. These strategies are not modified by the type of letter or its status.
There is relatively little visual reference to the town which is only looked at after reading the postal code. This is particularly interesting when compared with the version given by the operators who talk about the town as an additional source of information.

Also, the decisions made by the operators are cannot be reduced to the alternatives: postal code legible, letter indexed or postal code illegible, letter rejected (operating instruction). Operators set up processing strategies which enable them to extend their indexing possibilities.

This enables them to remove ambiguities linked to :
- technical problems: unfocussed, truncated or incorrectly displayed image,
- the address : code incomplete, erroneous, missing or illegible.

To achieve this, they use the whole of the destination line i.e. the code/town pairing. We might however say that the two different sets of information in the code/town pairing do not have the same meaning for the operator :
- The postal code is for the most part only significant from the point of view of its prefix which indicates a postal area. The rest of the expression has little meaning.
- The town brings together the whole group of information of cultural, affective, educational and professional origins, which strengthen its meaning.

Professional training (learning the names of postal areas and sub-areas) and the practice of manual sorting enable the operator to memorise a series of geographical entities composed of code/town pairings used to remove ambiguities. The association of these informational items enable him to make a judgement of coherence which will determine his decision.

The NAC recorder showed that certain operators frequently inspected the town name, on average once every four letters, whereas others talked about taking an overall view of the address. In fact, the focussing operations recorded by the NAC concern central vision.

The importance of visual perception in the task of video coding poses the problem of the contribution provided by peripheral vision in information gathering and processing mechanisms (Hella 1983).

This led us to make the assumption that the operator percieves part of the characters of the name of a town in addition to the postal code and that this enables him to detect any incoherences. The acquisition of information could be illustrated in the following way :

- If the graphical configuration of the name of the town complies with the representation or what is expected by the operator, indexing is possible ; in this case there is no focussing centred on the town.

- If the graphical representation of the town does not correspond to the expected representation, the operator will check code/town coherence by focussing on the town.

During our observations we noted that operating strategies varied as a function of time and fatigue felt by the operator. This explains why rejections are more frequent in the third hour of indexing.

It would have been interesting to investigate work performance data i.e. work output, the overall number of errors per operator, the number of errors compared to the duration of rest times, the type of errors, but these were not available.

CONCLUSIONS

In spite of the correct installation and equipping of the work station and the lighting environment, the video coding system in its present state shows inadequacies both from the point of view of structure and organisation of the task.
Insofar as the display is concerned, characters must have higher definition and a better character/background contrast provided with localisation of the image in the same spot each time.
As far as task structure is concerned, we would say that the operator has insufficient control of the system (he cannot correct coding errors and there are frequent and unexpected interruptions of the display).
The immobility of the operator accentuates the stress. The inadequacies of the video coding system were shown by the modifications required for certain indicators even after only 3-hour periods of work interrupted by 10 minute rest-periods.
The recording of visual strategies finally enabled us to demonstrate the relative complexity of information processing in what is, on the face of it, a very simple acquisition task.

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EYE MOVEMENTS: From Physiology to Cognition
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DESCRIPTION OF VISUAL "ACTION" IN "NATURAL" SITUATIONS

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This work concerns the question of interpreting visual behaviour in "natural" situations. One must cope with the relationship between vision and action and account for the meaning for the operator of what is perceived and what is done. We propose an action analysis framework to deal with such problems. We present the case of document processing with a microcomputer. A specific action model is briefly described. We show how this model enables us to interpret the structure of the behaviour (gaze-typing graphs), to situate the operator's decisions and to provide explanation for generation of incidents and for the operator's diagnosis concerning them.

INTRODUCTION

One is faced with two puzzling questions when attempting to understand visual behaviour in "natural" situations (in sport or work for example). First of all, it would be pointless trying to examine visual behaviour without taking into consideration what the subject does in other respects. However, for usual behaviour, the relationship between gazing and other aspects of behaviour is far from clear. In general, this relationship is analyzed in a rather rough and empirical way. Secondly, meaning has to be taken into account. This is the case when attempting to identify what is perceived or to define gaze status. Semantic aspects are usually mentioned without reference to any theoretical framework.
In conventional laboratory experiments, questions like these may be ruled out because of the way these experiments are designed : the meaning of the stimulus is greatly reduced and only visual scanning is analyzed. However, it is worth noting that these issues are not merely due to the practical needs of the analysis of "natural" situations. A perception theory as the ecological approach to vision applies to very closely-related problems (for instance, refer to Turvey, 1977, or Michaels & Carello, 1981). What we propose here is a theoretical framework which gives us an answer (or a partial answer at least) to these questions : we call it the ACTION APPROACH.

First, we shall give a quick rundown of the general characteristics of this approach, then we shall take an example of a particular study concerning a data entry activity. As such, we will be able to present the specific model of action. We will show how it can give some understanding of the behavioural structure as well as the subject's decisions and errors.

THE ACTION APPROACH

This is our starting point : in "natural" situations, observation alone is too weak to provide an interesting explanation of behaviour. At most, it may highlight some structural features of behaviour, but that only leaves us hypotheses to explain these features. We claim that we can get more powerful explanations by taking into account a forgotten source of evidence, namely the actor's intuitions about his action. The most significant of these are listed hereafter :

- the actor gives meanings to what he does or perceives (or at least part of this)
- he has conscious goals and plans ;
- he reasons out his actions and makes decisions concerning them ;
- he resorts to knowledge and relates his actions to previous experience ;
- he makes a distinction between a "correct" action and an error.

In addition, the actor has intuitive capacities : he can interpret actions in order to give an account of them or explain their reasons and goals.

We define a theoretical object -ACTION- in order to account for these intuitions. Compared to the traditional concept of BEHAVIOUR, ACTION should be seen as behaviour that is goal-directed, intentional, conscious, planned and socially controlled (refer to Cranach, 1982). It should be noted, in particular, that we make a clear separation between ACTION and the psychophysiological mechanisms underlying behaviour. We stress this point since the word "action" has been used on certain occasions merely to denote motor activity (for instance in Turvey, 1977 or Norman & Rumelhart, 1983). In this framework, we can say that ACTION is the meaningful part of activity or, in other words, we are interested in the cognitive and conscious aspect of behaviour.

ACTION is organized along two interrelated lines :
- sequentially in time : this is obvious. We shall consider the courses of action ;
- hierarchically : we must distinguish three interconnected organization levels : I. Meaning for the actor (knowledge), II. Cognitive guidance (partially conscious), III. Structure of the overt behaviour.

Our aim is to build a model of ACTION. This model takes into account the above-mentioned intuitions by including levels I and II. Unlike the "observational" approach, we do not limit ourselves to the hypothetical inference of the actor's strategies drawn from overt behaviour. The model represents generation of the overt behaviour structure.

The meaning always depends on a specific situation. Thus, we shall examine a particular study to show how this approach is pursued. To consider meaning requires detailed structural analysis of courses of action rather than a statistical study. We shall give examples of such analysis.

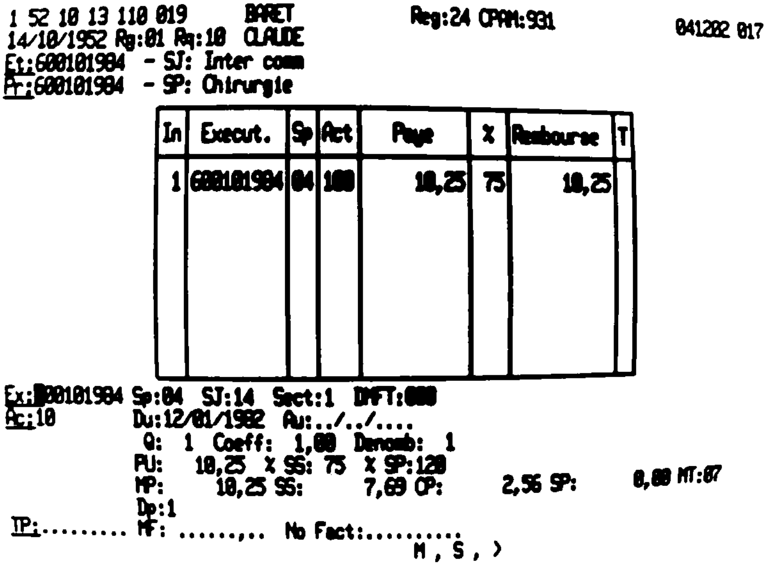
THE DOCUMENT PROCESSING SITUATION

In a Health Insurance Company, operators use a microcomputer. The computer software is designed to process the insured person's documents concerning medical treatment. The operator's activity represents an interactive and complex data entry procedure. In addition, she is the one who decides the reimbursement conditions on the basis of the regulations and with the aid of the computer.

Roughly speaking, she fills in a screen form (refer to figure 1) comprising various zones for identification numbers (e.g. Et, Pr and Ex), codes (e.g. Sp, SJ or Ac), calculation parameters (e.g. Q, Coeff, % SS), costs (PU, unit price) or amounts (MP, SS, etc...). The screen form is divided into different logical blocks (e.g. all the zones after Ex or the three zones : Q, Coeff and Denomb).

The theoretical paid amount or the percentage of expenses to be reimbursed is calculated automatically. The results are displayed in the zones MP, SS, CP and SP.

"Generating" programs automatically fill in the zones with the data already entered or with the most frequent values. Due to this feature, the operator need not type repetitive data such as the identification number of the insured person or the unit costs. If the operator agrees with the generated value, she can validate it simply by pressing the "Enter" key. If she agrees with all the values generated in a logical block, she uses the "block validation" function.



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1 52 10 13 110 019      BARET          Reg:24 CPAM:931          041282 017
14/10/1952 Rg:01 Rq:10  CLAUDE
Et:600101984  - SJ: Inter comm
Pr:600101984  - SP: Chirurgie
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In	Execut.	Sp	Act	Paye	%	Rembourse	T
1	600101984	04	100	10,25	75	10,25	

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Ex:█00101984 Sp:04  SJ:14  Sect:1  DMFT:000
Ac:10        Du:12/01/1982  Au:../../....
              Q:  1  Coeff:  1,00  Denomb:  1
             PU:    10,25  % SS: 75  % SP:120
             MP:     10,25 SS:      7,69 CP:     2,56 SP:      0,00 MT:07
             Dp:1
TP:......... MF: .......,..  No Fact:..........
                                        M , S , >
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Figure 1. The screen form.

An ACCOUNT corresponds to the section of the document which comes from the same doctor (identified in the Pr zones). This comprises different LINES. The zones from Ex down concern one line. Each line entered is summarized in the central table (refer to figure 1).

DATA ENTRY ACTION MODEL

At level III, we define theoretical notions in order to describe behaviour. As regards typing, we take into consideration the zones filled in (and their values), the use of function keys and the breaks in the typing sequence. As far as visual behaviour is concerned, we identify the point towards which the gaze is directed : the screen (S), the document (D), the keyboard (K) or elsewhere (E). Environmental features are also taken into consideration :

- the content of the document including the operator's notes ;
- the content of the screen, such as messages, values displayed in the zones, etc..

Unlike the "observational" studies, we introduce a meaning level (I). We rely on the "situation semantics" of Barwise & Perry (1983) for definition of our four central notions :

- event : everything that is present in the document or appears on the screen defined according to its meaning for the action. For instance, the fact that the paid amount on the document is more than the official rate means that the operator has to change the displayed value of MP (paid amount) (refer to figure 1).

- elementary actions: meaningful units of behaviour at our level of description of behaviour (typing and gaze). The meanings include designation of actions and the reasons for them (to which previous event or action they are related) and goals.

- concrete courses of actions and events : temporal sequences of actions and events.

- courses of actions and event-types (abbreviated to CAE-types) : abstractions of concrete courses of actions and events which let the operator classify them. We distinguish several ranks of meaning. Each rank includes the lower-order ones (figure 2).

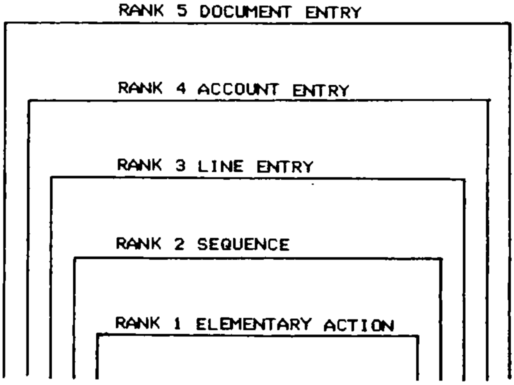


Figure 2. Ranks of courses of actions and event-types.

At any rank, different types have to be differentiated. For instance, at rank 3, one type consists of a sequence of block validations, another is characterized by modification of the COEFF and so on. The meaning of a given CAE-type includes the CAE-types in the higher order ranks to which they belong. The CAE-types monitor the concrete course of the actions and are at the basis of interpretation of events. Conversely, the interpretation of an initial event (in the document for instance) determines the CAE-type which the operator will follow. These CAE-types of different ranks capture part of the operator's data entry knowledge.

Now let us consider the cognitive guidance level (III). In the model, cognitive guidance is seen as the achievement of CAE-types. This consists of decision (like sequence triggering), event interpretation and adaptation (for instance, the correction of typing errors). The question of the operator's decisions is underlined below.

How does this model relate to data ? We use two kinds of collected data :
- video tapes showing the screen content and the operator's eyes.
These data concern the behavioural level ;
- "self-confrontation" verbalizations : immediately after the session, the videorecordings are shown to the operator. She is questioned about incidents, gazes and breaks while typing. These data refer to the operator's intuitions.
The observational data are used to produce gaze-typing graphs (refer to figures 4, 5, 6 and 7). The meanings of actions and events are determined at different ranks on the basis of a web of inferences. These inferences take the following into account :
- what the operator tells us : non-overt activities (e.g. "I'm calculating the coefficient"), designation of action, reasons and goals of action.
- features of the graphs : mainly the relationship between gaze and typing.

CONTRIBUTIONS OF THE MODEL

In order to show the relevance of this model, we will consider three aspects : (1) interpretation of the structure of overt behaviour ; (2) the operator's decisions and (3) the incidents.

Interpretation of the structure of behaviour

By comparing the different graphs, we find patterns corresponding to behavioural regularities. How can these patterns be explained by our model ? We shall take an example concerning line entry.

Example :
When the operator processes lines including a modification of the coefficient, her behaviour presents some regularities (refer to figure 3) : she looks at the document before typing the date ; she looks at the screen when moving to the COEFF zone, then she looks at the documents, etc...

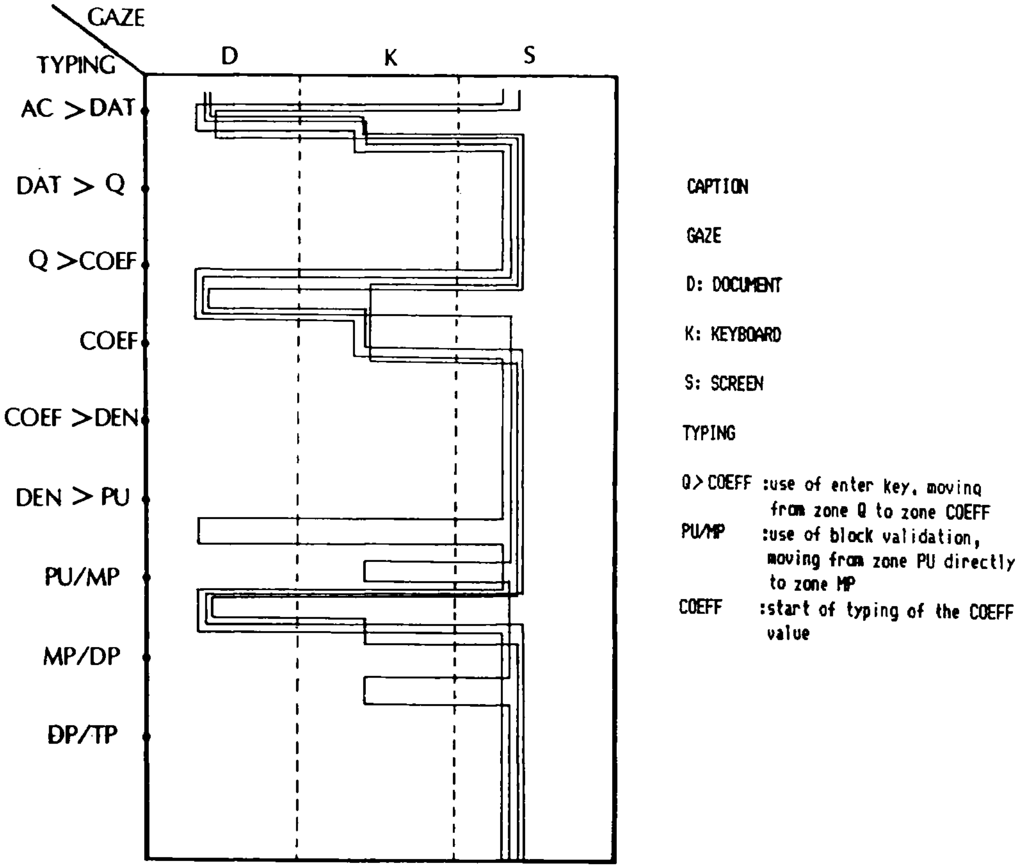


Figure 3. Lines with a change of coefficient (this diagram does not consider the duration of gazes but only the sequence ; each path refers to the processing of a single line).

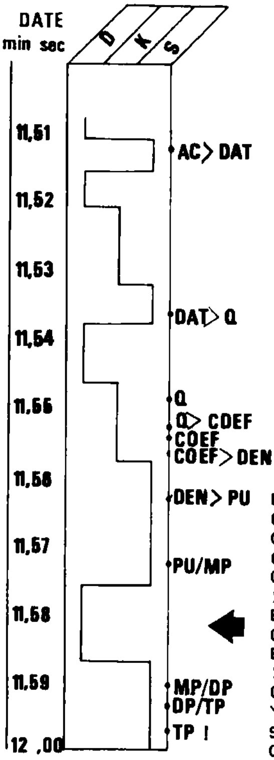
Some features of this pattern are easy to explain through a simple examination of the relationship between gaze and typing : for instance, the operator looks at the document to pick up an item of information in order to type it (the date, the coefficient, etc...). But for some features, the interpretation is not straightforward. For instance, it is difficult to obtain a precise interpretation of the break at MP (between PU/MP and MP/DP) and the gazing at the document which occurs during this (the MP zone corresponds to the paid amount). We are going to show how it is possible to construct the meaning of such elementary actions.

Let us take the example of all the breaks at MP which appear in our collection of graphs. Two features around the break in each graph have to be considered : (a) whether or not the document is gazed at and (b) whether or not the value for MP is typed. The conclusions we can draw from these observational data alone are inconclusive or vague. For instance, if the operator does not look at the document, we are lost in conjectures about the interpretation of the break at MP.

Fortunately, through an examination of the verbalisations, we can give four different meanings to the break MP :

(1) Verification of the paid amount in order to check typing of the Q and COEFF values.
(2) Verification of the paid amount in order to check that the microcomputer has rounded off the amount in the same way as the person who filled in the document (this verification concerns the digit for centimes).
(3) Whether or not a decision is made to change the value at MT (which is at the end of the MP block - refer to figure 1).
(4) Acquisition of the paid amount on the document in order to change it in the MP zone.

Example : Figure 4.



E: YOU STOP A LITTLE AT MP ?
O: YES, BECAUSE THERE WERE A QUANTITY AND A COEFFICIENT TO CHANGE, I HAD TO PUT 10 IN QUANTITY AND 6 IN COEFFICIENT. SOMETIMES WE GET MIXED UP, THEN WE LOOK AT THE MP. HERE IT'S 627 F., IT'S O.K.
E: SO IT'S INDEED THE PAID AMOUNT YOU LOOK AT
O: OH! YES IT IS THE PAID AMOUNT.
E: YOU DON'T CHECK OUT THE NUMBERS YOU TYPED IN BEFORE ?
O: OH! NO,NO, I CHECK OUT THE PAID AMOUNT, YES ... WE ARE SO MUCH IN A HURRY THAT SOMETIMES ... WE PUT THE QUANTITY IN COEFFICIENT ZONE OR CONVERSELY, AND AT THE END THE PAID AMOUNT IS WRONG.

Figure 4. An example of a break at MP.

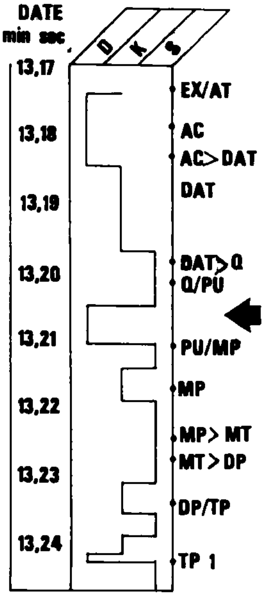
In figure 4, we give an example of Type (1). The operator breaks the typing sequence when she arrives at MP (11.57) then looks at the document and finally validates the block (11.59). The verbalization indicates the type of verification made by the operator.

The different meanings we have identified are related to previous parts of the course of action (1 and 2) or subsequent parts (3 and 4). Here, we can see how the meaning of elementary actions refer to the CAE-types at the higher order ranks.

The operator's decisions

At some points in the course of action, elementary actions may differ, depending on the CAE-types executed by the operator. The model implies that the decision to carry out such and such an action may be made previous to these points : this represents triggering of the execution of a particular CAE-type. This accounts for behavioural regularities.

Example :
For the reimbursement of consultations, the operator has to check whether or not the paid amount exceeds the official rate. If it does, she must change the value displayed at MP. So the question is : when does the operator make the decision ?



E:YOU STOP ON P.U. ZONE ?
O:IT'S IN ORDER TO CHECK OUT WHERE IS THE CURSOR BECAUSE I HAD TO CHANGE THE MP.

Figure 5. A consultation where the paid amount exceeds the official rate.

Figure 5 shows the graph and the verbalization for processing of a consultation where the paid amount exceeds the official rate. There is an initial break at PU (unit price). The verbalization suggests that this break does not correspond to a decision but to preparation for the "change the MP" action. This is confirmed by an examination of the operation for processing a consultation amount which does not exceed the official rate.

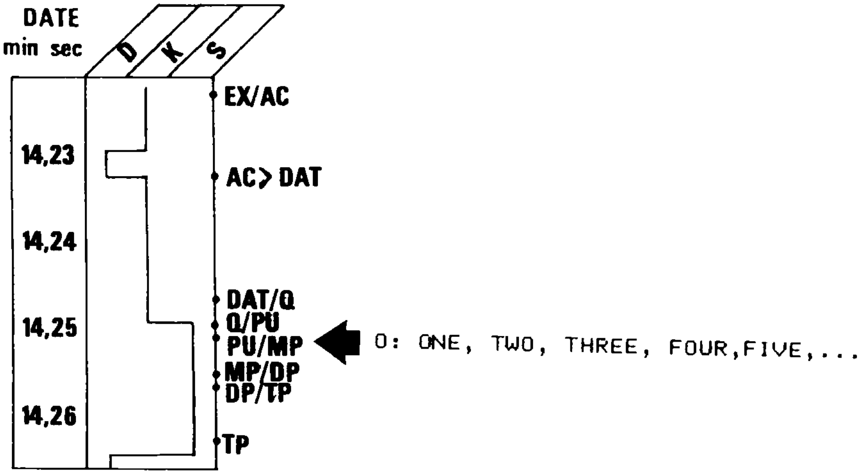


Figure 6. An ordinary consultation.

In figure 6, we can see that after the move to Q block (14.25) the operator completes a continuous sequence of block validations. The verbalisation describes this sequence (by counting the function keystrokes). This fact proves that the operator has decided not to change the displayed paid amount before arriving at MP. It should be noted that since we have defined several meaning ranks, we have to consider that these desisions take place at several corresponding ranks.

Incidents

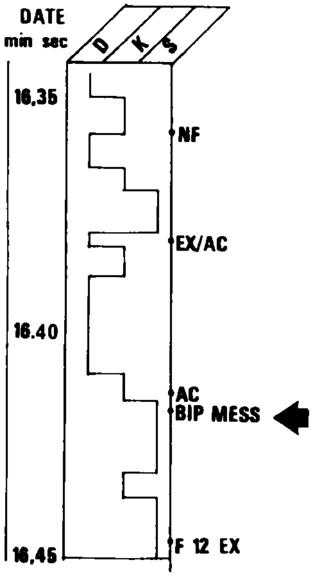
The model provides an explanation for the generation and the operator's diagnosis of two important types of incident : forgetting the change of displayed values and errors when filling in the zones (including misuse of functions).

Generation :

Usually, these incidents are attributed to vague factors : carelessness, lack of concentration, force of habit, etc... However, it is noticeable that the operator does not type just anything. As Young & O'Shea (1981) pointed out, it is more fruitful to regard the operator as faithfully executing a faulty procedure than as wrongly following a correct one. According to our model, the erroneous action can be considered as resulting from confusion between similar CAE-types which have common parts, for instance. This interpretation is similar to the so-called "capture errors" analyzed by Norman & Rumelhart (1983) : these occur "when there is an overlap in the sequence required for the performance of two different actions".

Operator's diagnosis

If we examine how the operator diagnoses the incident, it can be shown that she thinks of the correct CAE-type in order to interpret the event.



MESSAGE : "TOUT EXECUTANT INTERDIT
AVEC CET ACTE "

("EVERY PERFORMER FORBIDDEN WITH
THIS ACT CODE ")

O: I PUT ACT CODE 30 WHEREAS IT IS 31 / WHEN IT IS A MUTUAL BENEFIT PHARMACY THERE SHOULD BE A PERFORMER.
E: THEN, HERE, YOU CHANGE THE ACT CODE ?
O: THE ACT CODE / I PUT 31 INSTEAD OF 30.

Figure 7. An incident with a message.

Figure 7 shows an incident during the processing of a pharmacy invoice. An error message appears just after the act code has been typed. The code 30 represents an ordinary pharmacy and the "performer" block (Ex) has to be left blank. In this case, the operator has validated the Ex block (at 16.38).
As regards generation, we developed the following analysis. The erroneous action at zone AC is not a simple typing error. Two different CAE-types have been confused : the operator began with a mutual benefit pharmacy and then carried on with an ordinary pharmacy (which is more frequent). What could be said about the operator's diagnosis ? The message only indicates incompatibility between the filled-in Ex blok and the act code 30. The meaning assigned to the message ("change the act code") refers to the CAE-type at execution. This analysis of the operator's diagnosis accounts for the fact that she does not look at the document in order to decide what has to be done.

CONCLUSION

What is the practical aspect of such an approach as far as ergonomic transformations are concerned ? Usually, the analysis of data entry work provides designers only with very general hints. Due to the highly detailed analysis we carried out and the models we produced, we were able to draw up very specific transformation proposals. Their presentation would be beyond the scope of this paper. Suffice it to say that the improvements not only concern the computer software but also the training, since we identify some important aspects of operative knowledge (Pinsky & Theureau, in press).

In a more general sense, what is the part played by the study of eye movements in analyses concerning "natural" situations ? Very often (as in the examples presented here) the definition of improvements requires a careful explanation of visual activity to establish the relationship relative to situational constraints. We hope to have demonstrated that this explanation must take into consideration ACTION as a whole.

Conversely, an analysis of eye movements is of great importance in order to understand ACTION. What is stressed here is the necessity to develop a proper theoretical framework concerning "vision in action", apart from the dialectical relationship between visual scanning research and applications.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

EYE MOVEMENTS AND TASK DEMANDS ON VDU

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The relationships between eye movements and task demands on VDU were investigated in : (a) real work situations and (b) laboratory experiments.
In (a), data entry operators showed a higher eye scanning rate, a lower duration of uninterrupted regards at the screen and higher amount of reported visual strain symptoms than dialogue operators.
In (b), subjects performed a data entry task for two hours in two experimental conditions : at their own pace and under time pressure.
In the time pressure condition, performance, error rate, EEG beta index and heart rate were significantly higher than in the self-paced condition. The rate of screen-directed eye movements significantly decreased under time pressure.
Conclusions : 1. The ocular discomfort experienced by data entry operators may be related to the scan rate rather than to the time spent viewing the video display. 2. The work under time pressure induced a state of stress evidenced by an increase of the physiological arousal and a change of the subject's information processing strategy. The eye movement measures provided an objective indication of this change.

INTRODUCTION

The analysis of the manner in which operators' eyes move and fixate may give an indication of the allocation of attention among various information sources. For video display unit (VDU) tasks, there are three main sources of information : the hard-copy material, the video display, and the keyboard. The percentage of time that subjects look at these areas differs from task to task.

In data entry work, operators transfer information (numbers, letters or symbols) from the source-document to the computer in a repetitive manner ; the work pace is high but the task does not require frequent looking at the video screen. The average percentage of time the operators look at the screen is rather low. As observed by Elias & Cail (1982), the screen inspection time represented 15 - 25 % of the work time. In experimental conditions, Zwahlen (1983) found that subjects look at the screen 14.4 %, at the document 54.7 % and at the keyboard 27.6 % of the work time on average.
Interactive communication (conversational or dialogue) involves less use of a source-document ; the task is likely to be more screen-intensive. Operators sustain a dialogue with customers or/and computer and have some opportunity of decision making. The average percentage of time the operators look at the screen is quite high ; it varies from 35 % to 80 % (Elias & Cail, 1982).

Word processing mainly involves text entry and error correction. Text entry activity is document-intensive, similar to data entry ; searching text for errors and keying in corrections are screen-intensive. Word processing jobs usually involve different combinations of these elements at different times (NRC Panel, 1983). An analysis of the operator's activity in a newspaper company using VDUs showed that the scanning rate increased with the difficulty of the task ; the fixation time was higher in the correction than in the text entry task (Duraffourg, J., Guerin, F., Jankovsky, F. & Pavard, P., 1979).

Several surveys of VDU operators showed that data entry and clerical operators reported a significantly higher amount of visual, postural and nervous symptoms of strain than dialogue ones (Elias, R., Cail, F., Tisserand, M. & Christman, H., 1980) ; Johansson and Aronsson, 1980 ; Smith, M.J., Cohen, B.G.F., Stammerjohn, L.V. & Happ, A., 1981). Besides important environmental and psychosocial factors affecting the stress experienced by VDU operators, those related to the nature of the task and work rate were often mentioned.

The main purpose of this study is to point out the value of eye movement measurement for evaluating some features of the task demands on VDU, namely those related to the nature of the task and work pace.

As concerns the nature of the task, one objective of this study was to find some relationships between task demand and eye movement pattern that could account for the widespread ocular and visual complaints reported by the data entry operators. Accordingly, we compared eye movement recordings for data entry and dialogue operators in real work conditions.

Data entry tasks entail rigid work procedures with high production standards and constant pressure for performance. The fast work pace and boring repetitive task are considered as the major sources of operator stress (Smith, op.cit, 1981). Thus, another objective of our study was related to the work pace in data entry tasks. We supposed that an increase in the work pace resulted not only in quantitative changes of the eye movement pattern but also in qualitative ones, revealing some alteration in the operator's strategy. This hypothesis was tested through laboratory experiments. In these conditions behavioral and electrophysiological variables were recorded continuously during a simulated data entry task under self-paced and time pressure conditions.

METHODS

1. In the field investigation, a questionnaire survey was used for gathering information about the subjective visual symptoms of strain in two groups of 89 data entry and 71 dialogue operators from several workplaces.

A sample of 14 subjects from the first group and 24 for the second one were tested before and after work in order to obtain measures of eye muscle balance (lateral phoria at 5 m optical distance), visual reaction time (RT) and near point of accommodation.

The NAC Eye-mark-recorder was employed to measure eye movements in six data entry and seven dialogue operators for 30 min of continuous work.

2. For the laboratory research, an experimental VDU station was built in the laboratory. In order to minimize the factors of constraint not directly related to the task, the ergonomic requirements concerning environmental conditions, display and work place were observed. The display screen was adjusted for optimal legibility (negative contrast, lack of glare, no reflections or luminance oscillations). All the components of the workplace (supports for VDU, keyboard, and source document, chair and backrest) were independently adjustable.

After several training sessions, subjects performed a data entry task (DET) that consisted of transferring the numerical data of about a thousand cheques to the terminal through the keyboard ; they had the opportunity of correcting errors before storing the data (for details about methods cf. Floru, R., Cail, F. & Elias, R., 1985).

Behavioral responses (performance, errors) and physiological ones [spectral analysis of the occipital electroencephalogram (EEG), heart rate (HR) and elecro-oculogram (EOG)] were continuously recorded. For EOG recording, three small size skin electrodes (Beckman) were attached with adhesive collars binocularly at the outer canthi and above the right eyebrow. This arrangement enabled us to distinguish between control-correction eye scanning, that is, eye movements between screen and keyboard (SK), and short glimpses, that is, eye movements between screen and source document (SD) ending a work cycle (fig. 1).

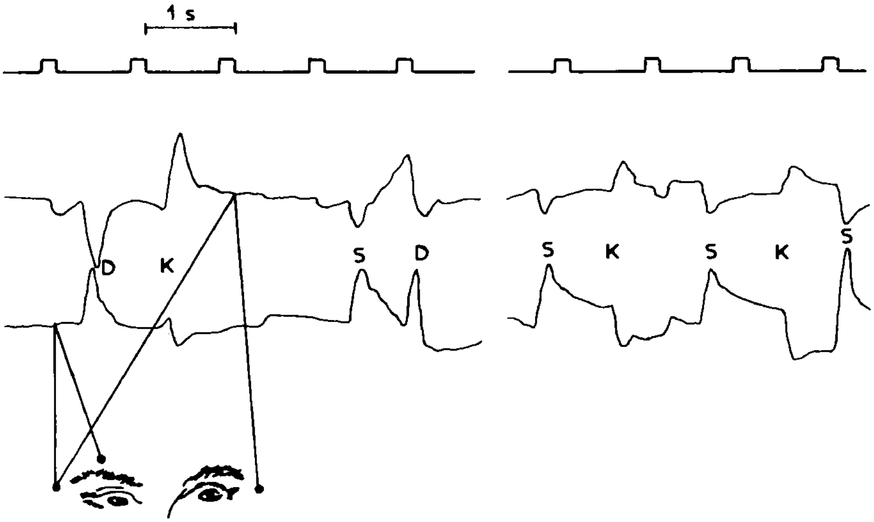

Figure 1 : Electrooculogram in data entry task
S : screen ; D : source-document ; K : keyboard

A first series of experiments was carried out in order to evaluate the learning effect on psychophysiological variables. Seven subjects performed the DET at their own pace for two hours in two separate sessions spaced 6-7 days apart.

In the second series of experiments ten subjects performed the DET for two hours under two experimental conditions : (a) self-paced (SP) and (b) under time pressure (TP) elicited by material incentive.

RESULTS

1. The most striking result of the field study is revealed by the relationship between the nature of the task and the eye movement patterns. Comparison of eye movements in the data entry task (DET) and dialogue task (DT) shows significant differences in scan rate and fixation time (fig. 2).

Figure 2 (A) shows that the rate of screen-directed regards is higher in data entry than in dialogue operators (t = 6.12 ; $p < .01$) whereas the average duration of an uninterrupted regard (B) is higher in dialogue than in data entry operators (t = 8.88 ; $p < .01$).

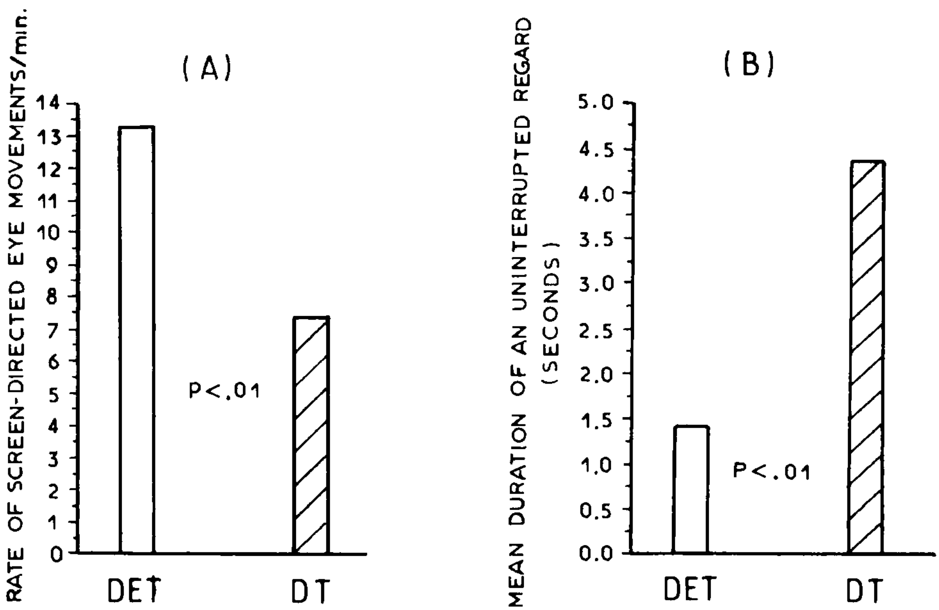

Figure 2 : Eye scanning behavior in VDU task
(A) : rate of screen-directed eye movements ;
(B) : average duration of an uninterrupted regard at the screen ;
DET : data entry task ;
DT : dialogue task.

As concerns the other results, the DET operators reported a significantly ($p < .01$) higher amount of visual and ocular discomfort than DT ones. Yet, the pre/post work differences for the near point accommodation, phoria and visual RT could be related not only to the nature of the task but also to the work duration.

2. In the laboratory experiments, the comparison between the average values of psychophysiological variables scored in the first (test) DET and second (retest) sessions shows significant differences for performance, eye movement rate, HR and beta index. No significant differences were found for error rate and theta index (fig. 3).

Figure 3 indicates a significant increase of the mean values for performance (t = 7.66 ; $p < .05$), SK rate (t = 5.45 ; $p < 0.1$), SD rate (t = 5.14 ; $p < .01$) and beta index (t = 2.10 ; $p < .05$), significant decrease of HR (t = 3.11 ; $p < .01$) and non significant decrease of error rate in the retest session as compared with the test one.

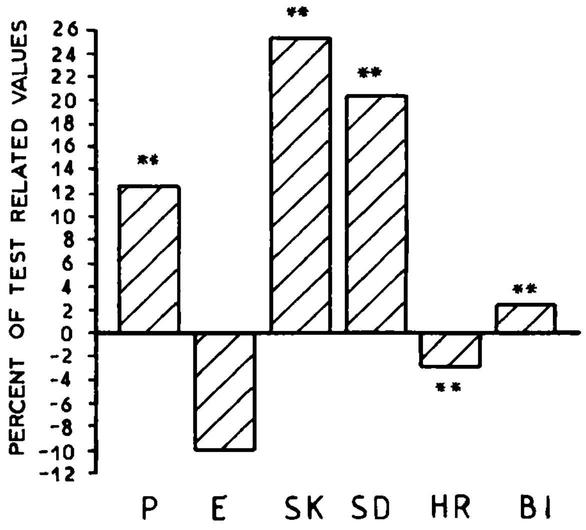

Figure 3 : Mean changes of psychophysiological variables in the retest self-paced DET session. All values are given as a percentage of the test session values.
P : performance ; E : error rate ; SK : screen-keyboard eye movement ; SD : screen-document eye movement ; HR : heart rate ; BI : beta index. ** $p < .01$.

In both test and retest experiments there are significant ($p < .01$) positive correlations between performance and beta index and negative ones with theta and alpha indices. SK show significant positive correlations with theta index and negative ones with performance whereas SD show positive correlations with performance ($p < .01$).

3. The comparison of the average values of psychophysiological variables scored in the self-paced (SP) and time pressure (TP) conditions shows significant differences for performance ($t = 20.49$; $p < .01$), SK rate ($t = 7.71$; $p < .01$), SD ($t = 8.56$; $p < .01$), HR ($t = 10.27$; $p < .01$) beta index (t 6.11 ; $p < .01$) and theta index ($t = 4.24$; $p < .01$).
Figure 4 indicates that overall performance level, error rate, HR and beta index are higher whereas the eye movement rates are lower in the TP than in the SP condition.

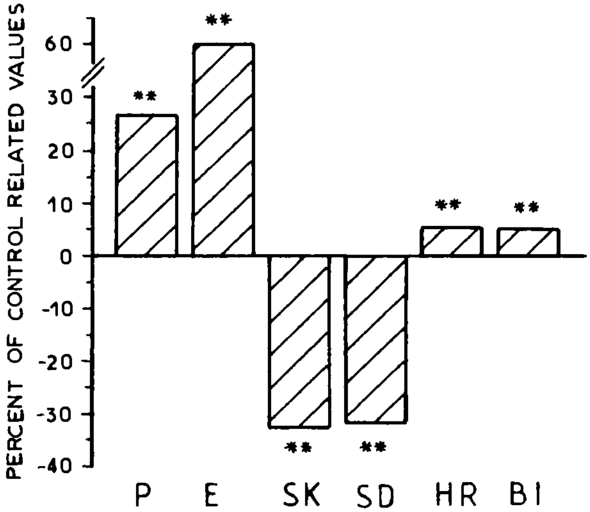

Figure 4 : Data entry task. Mean changes of psychophysiological variables in the time pressure condition. All values are given as a percentage of the self-paced condition.

DISCUSSION

It is well known that prolonged work at VDUs leads to symptoms of eye strain and visual discomfort. These symptoms seem to be related to the task demands. Some surveys have reported that complaints of ocular discomfort increase with increased percentage of work time spent working with VDUs (Rey and Mayer, 1980 ; Dainoff, M.J., Happ, A. & Crane, P., 1981). Though, no significant differences between VDU and non-VDU operators were found in visual tests (visual acuity, lateral and vertical phoria) measured before and after work (Dainoff, 1980 ; Dainoff, op.cit., 1981). As concerns the nature of the task, the comparison between data entry of clerical operators and interactive or dialogue ones have shown a prevalence of ocular and visual discomfort in the former group (Elias and Cail, 1982 ; Smith, op.cit., 1981). Yet the before/after work measures did not show differences that could be related to the nature of the task exclusively. In a critical review of experimental field and laboratory studies on visual problems related to VDU work, the panel members of the National Research Council concluded that job and task analysis ought to take into account the visual requirements placed on the operator. "Such analysis would consider how the eye must be used to perform the task required" (NRC Panel, 1983, p. 147).

In our field experiments the eye movement measures show a significantly higher scan rate and a lower duration of uninterrupted regard at the screen in data entry operators than in dialogue ones. Consequently, it seems improbable that the prevalence of visual and ocular symptoms reported by data entry operators could be related to the screen itself. Zwahlen (1983) also concluded that the amount of time looking at the screen has no major influence on visual comfort.

We may therefore suppose that the main factor of constraint in DET is more related to the repetitive eye movements between the video screen and hard-copy material than to the duration of screen inspection. Accordingly, there are repetitive demands upon the mechanisms of eye accommodation, imposed by the two fixed distances (eye-source document and eye-display), and the alternative retinal adaptation to the positive (source documents) and negative (display) contrasts of luminance. The short work-cycle that characterizes the data entry task imposes a high rate of document-screen eye movements, thus contributing to the ocular and visual discomfort.

Two issues stand out when examining the results from the laboratory experiments. First, when subjects are trained to work in a self-paced condition no strategy change can be observed, whereas time pressure induces a change in the operator's strategy. Second, the eye movement measures were the unique indicator of such a change. Indeed, in both retest SP session and TP condition, performance and cerebral arousal change in the same direction while opposite direction changes occured in eye scanning rate.

The test-retest experiment shows, as expected, a learning effect evidenced by a significant increase in performance and a slight decrease of error rate. Subjects better control their entries : a computed control-correction index (SK/-performance ratio) is significantly ($p < .05$) higher in the retest session than in the test one.

The positive correlation between SK rate and theta index as well as the negative ones between SK rate and beta index indicate that the lowering of the arousal level is accompanied by an increase of corrected errors. The arousal level also shows positive correlations with performance, i.e. direct correlations of beta index and HR and inverse ones of theta and alpha indices with performance.
We may suppose that at a certain degree of deactivation, the subject is still aware of his errors and corrects them ; this leads to an increase of "correction" eye movements. He also becomes more cautious ; this probably increases the "control" eye movements. Unfortunately, we had no possibility to distinguish between these two categories and designated all the eye movements between screen and keyboard as " control-correction" eye movements.

Under time pressure a learning effect cannot be disregarded, since performance increases. Nevertheless in the TP condition as compared with the SP one, subjects are working under stress evidenced by the significant increase of the cerebral (EEG) and autonomic (HR) arousal. If we compare the change of HR from test to retest self-paced condition, and that from SP to TP condition, we observe that in the first case HR significantly decreases whereas in the second one it significantly increases. Therefore, under the TP condition subjects are actually stressed.
The significant reduction of the SK and SD eye movement rate may be interpreted as a change in information processing strategy. Subjects under stress by-pass a whole information processing link in order to increase the work output. They reduce the control of the data on the screen but allocate their attentional effort on reading and typing, thus preserving a high performance level. Indeed, a computed speed-accuracy index, that is performance/error rate ratio does not change significantly.

The increase of the performance under time pressure denotes a shortening of the work-cycle. It results not only from discounting the "scanning time" but mainly from a removal of a cognitive loop.

Our general conclusion is that eye movement measures enlarge the possibilities of psychophysiology in VDU studies in two ways. First, they provide relevant information about visual requirements related to the characteristics of the task (content of the task and/or time pressure). Secondly, in work under real conditions they provide an objective indicator of presumed mechanisms of ocular discomfort.

Acknowledgement

The authors are indebted to J.C. CNOCKAERT, J.J. VOGT and M. NEBOIT for their valuable comments on a previous version of this paper.

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sample of pseudo text with fixation marks

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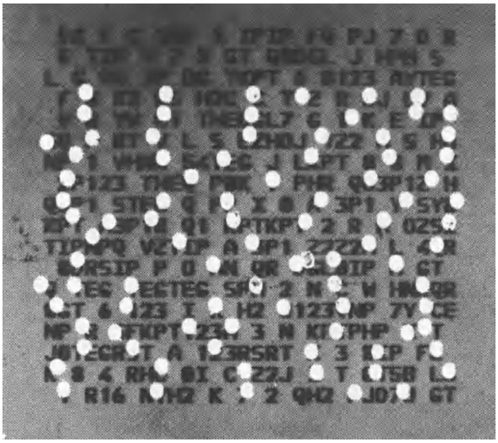
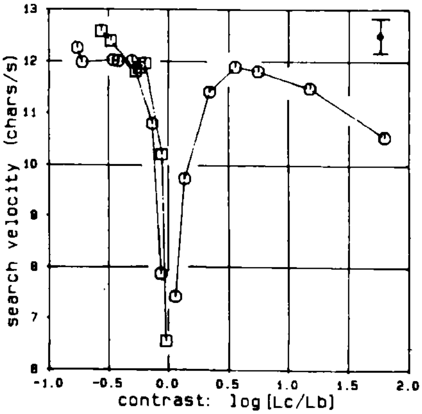


Example of fixation pattern (white spots) searching for the letter 'A'. The eye movements were recorded, starting from the fourth line. The angular width of the characters was 14 arcmin. The descender width was 1.7 arcmin.

correlation of the objective variables with judgement:
r=0.87 +/- 0.03

2. search velocity

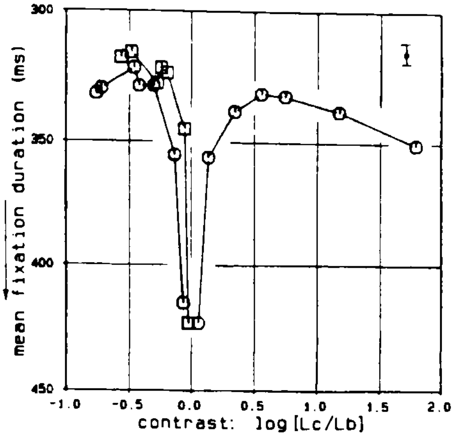
3 subjects; 4 presentations; N=12
○: mean luminance = 40 cd/m**2
□: mean luminance = 200 cd/m**2



Velocity of search for the character 'A', expressed in number of scanned characters per second, as a function of the log of the luminance contrast ratio.

3. fixation duration

3 subjects; 4 presentations
○: mean luminance = 40 cd/m**2
□: mean luminance = 200 cd/m**2



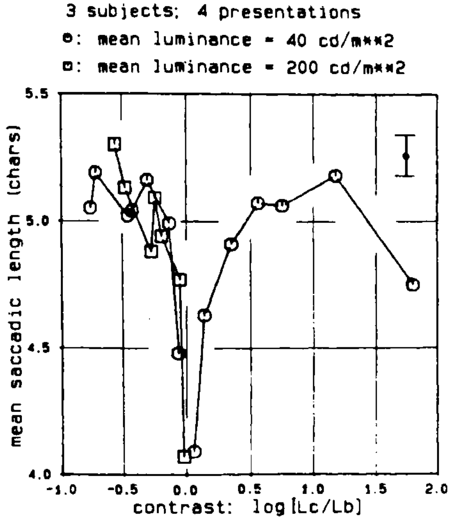
Fixation duration as a function of the log of the luminance contrast ratio. Short fixation durations correspond to fast information intake. Note the reversal of the usual ordinate direction convention.

Eye movements, performance and visual comfort using VDTs

Conclusions:

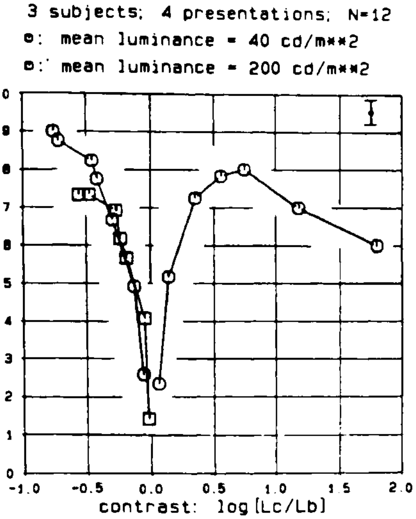
- High correlation of scaled visual comfort with fixation duration, saccadic length and search velocity, which are considered to be measures of the ease of information intake.
- There is an optimal positive contrast at a contrast ratio of about 5. Probably, also an optimal negative contrast exists at a ratio of about 1/5.
- Negative contrast seems slightly better.

4.
saccadic length



Saccadic length as a function of the log of the luminance contrast ratio. The more difficult to read, the smaller the saccades are.

1.
comfort judgement



Comfort judgement on a 10 point scale as a function of the log of the luminance contrast ratio. Positive values correspond to "positive contrast" (Lc is character luminance, Lb is background luminance).

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VISUAL SCANNING AND AGE

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INTRODUCTION

Many studies showed changes in perceptual processes with age at peripheral as well as at central stages (FOZARD, WOLF, BELL, Mc FARLAND & PODOLSKY, 1977).

Unlike the separate study of perceptual capacities, the analysis of visual scanning can give valuable information on the strategies used by middle-age and older people in order to compensate

THE FIRST EXAMPLE **concerns tractor driving : visual exploration by 16 tractor drivers was observed during ploughing tasks, according to a method described in a previous paper (MARQUIE & CELLIER 1983). Half of them were under forty and the others were over. All were skilled and had equivalent equipment.**

Results show that older drivers have a higher level of exploratory activity and do not have the same visual scanning pattern : their gazes are significantly more centred on the information directly linked to the task.

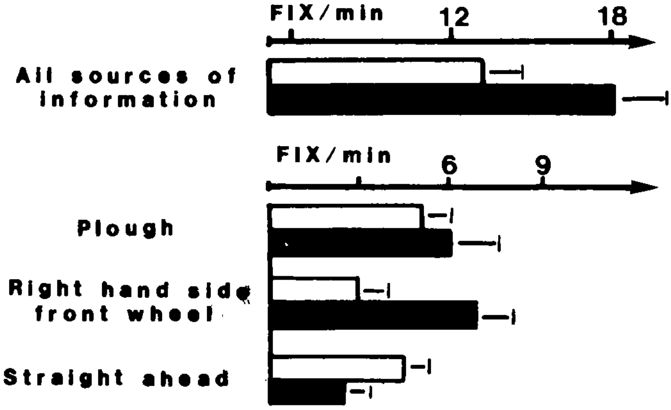

Figure 1
Mean frequency (and S.E.) of glances towards various information sources in tractor drivers, according to age :
- under the age of 40 (mean 28,6) ; Blank histograms.
- over the age of 40 (mean 49) ; Shaded histograms .

CONCLUSION

As well as their particular meaning, these results, taken in two different situations, underline the different ways in which young and older adults may select the surrounding signals. Considering the equivalent subjects' experience, one may think that such differences show criterion changes and compensations of the effects resulting from the evolution of visual perception with age.

IN DIFFERENT TASKS

---

changes occurring in their sensory and processing information systems.

This can lead to conceptions and adaptations including and increasing these possibilities.

The aim of this paper is to bring out differences in young and older adults with similar occupational experience, as shown by some research results.

RESULTS

THE SECOND EXAMPLE concerns the activity of sticking pins according to a given pattern set on display 1.80 m. away from the subject. The subject could not control his hand movements because of a cover. The display also informed the subject about the accuracy of his action by switching on a corresponding light.

A double video device recorded the direction, frequency and duration of the gazes. Thirty four subjects separated into four age groups performed the same task.

Results show that older people spend a longer time looking away from the display towards their hands (which they cannot see).

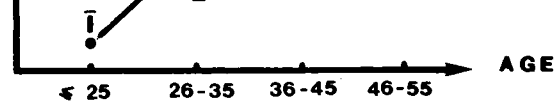

Figure 2
Time spent (%), according to age in a pin sticking task without any possibility of visual control of action , looking away from the display towards one's hands or an intermediate zone.

In ergonomics, one must take these changes into account in order not to impose on the operator processing modes which would not be adapted to his own working mode.

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ANALYSIS OF VISUAL PATTERNS OF TABLE TENNIS PLAYERS

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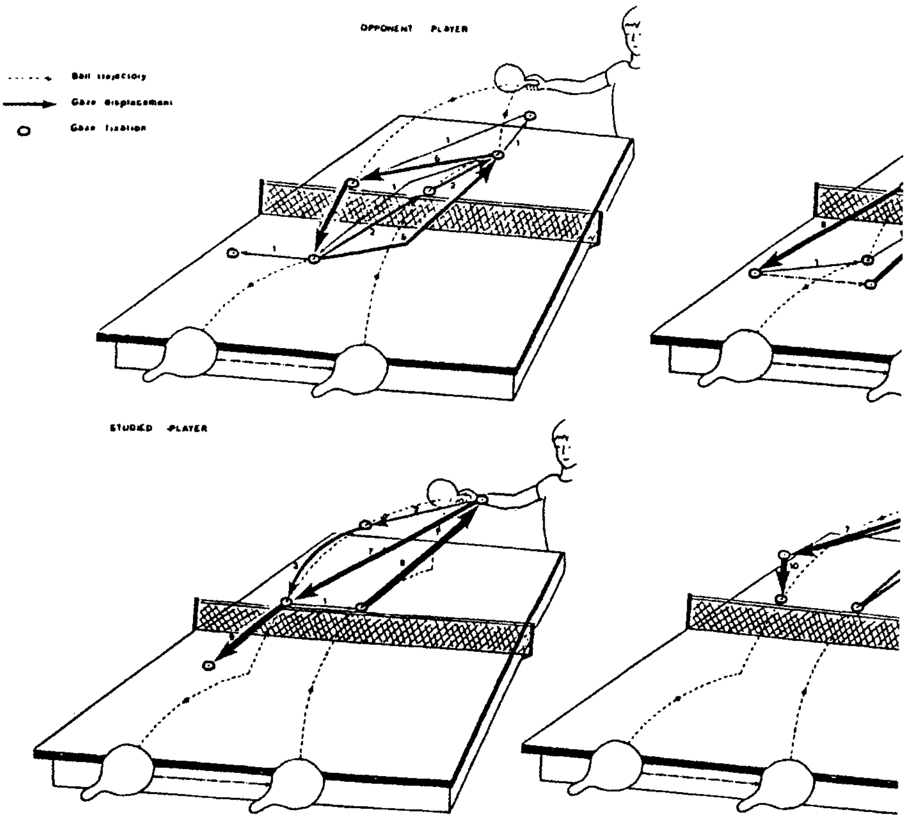
PURPOSE OF THE STUDY

THIS STUDY WAS UNDERTAKEN TO IDENTIFY THE VISUAL SCANNING PATTERNS OF HIGH LEVEL TABLE-TENNIS PLAYERS .

THE VISUAL BEHAVIOURS WERE STUDIED BY USING A VIDEO-OCULOGRAPHIC TECHNIQUE TO RECORD THE DIRECTION OF GAZE (NAC EYE MARK RECORDER).



THE FIGURES 1 TO 5 SHOWS THE FLOW DIAGRAMS STRATEGIES OF THE 5 PLAYERS. THE THICKNESS OF THE ARROWS IS IN DIRECT PROPORTION WITH THE FREQUENCY OF THE ASSOCIATION OF TWO SUCCESSIVE ELEMENTS. THE NUMBER INDICATE HOW MANY TIMES ($n = 10$).

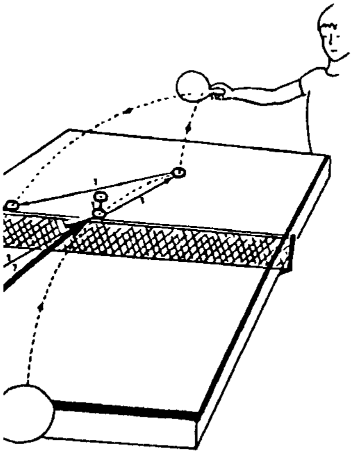
PROCEDURES

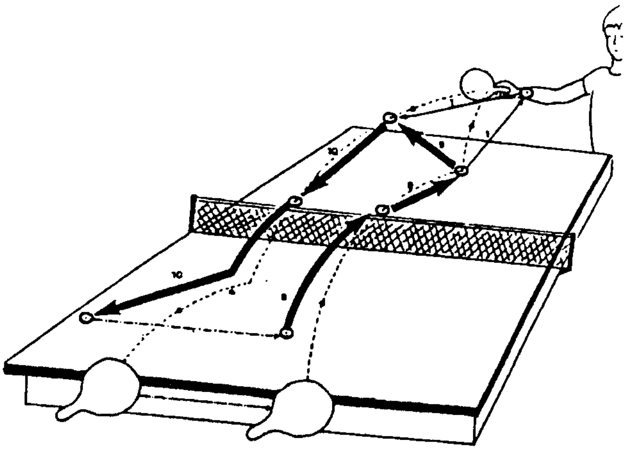
THE SCANNING PATTERNS AND THE MOTOR BEHAVIOURS WHERE SIMULTANEOUSLY RECORDED AND THEIR INTERACTION ANALYSED.

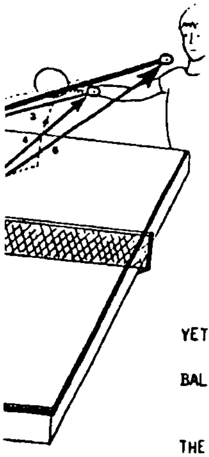
5 FRENCH INTERNATIONAL TABLE TENNIS PLAYERS WERE STUDIED IN TEN SUCCESSIVE FOREHAND STROKES.

A SEMI-COMPUTERIZED METHOD OF DATA COLLECTION PERMITTED THE ANALYSIS OF :

- THE IDENTIFICATION. THE TIME DURATION AND THE CHRONOLOGY OF VISUAL FIXATIONS ;
- THE BALL TRAJECTORY ;
- THE MOTOR BEHAVIOUR OF THE PLAYER.







RESULTS

THESE RESULTS PERMIT US TO CONCLUDE THAT EACH PLAYER HAD HIS OWN SCANNING PA YET WE DESCRIBE SOME CONSTANT MECHANISMS.

- THE BALL IS NEVER TO VISUALLY TRACKED EXCEPTED FOR THE PLAYER 3 WHO TRACKS BALL A BRIEF PERIOD JUST BEFORE HITTING.
- THE GAZE IS FEW DIRECTED ON TO THE OPPONENT PLAYER.
- THE PLAYERS DEMONSTRATED A HIGH LEVEL OF ANTICIPATION-COINCIDENCE BEHAVIOU THE RELEVANT INFORMATION ABOUT THE BALL TRAJECTORY IS EXTRACTED IN POSITIONNING THE GAZE SOME CRUCIAL POINTS. PASSAGE OF THE BALL OWER THE NET AND THE BOUNCE ON THE TABLE. THIS INFORMATION OF POSITION IS ANTICIPATED AND THE LINE OF VISION DIRECTED ACCURATELY AT THE PREDICTED POSITION. THIS VISUAL INFORMATION IS NEEDED TO EXECUTE THE VISUO-MANUAL COORDINA WITH ACCURACY. EXCEPTED FOR ONE PLAYER (5), ALL PLAYERS FIXED THEIR LINE OF VISION CLOSE T BOUNCE POSITION. FROM THIS MOMENT ONE. THE LINE OF VISION IS ALWAYS FIXED INSIDE THE HEAD. THE FUTURE COORDINATION BETWEEN THE BALL AND THE BAT IS EXECUTED ON THEIR LINE OF VISION.

WE THINK THAT THIS EYE/HEAD COORDINATION PROVIDES A FIXED REFERENCE FOR THE SUBSEQUENT ROTATION OF THE SOULDERS AND THE BODY AND THE CORRECT EXECUTION OF THE RETURN.

EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

RECORDING EYE MOVEMENTS BY ULTRASONIC METHOD

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To record movements of closed eyes, EOG seems to have been the only method. In this study, applying the ultrasonograph developed with clinical aims, closed-eye movements were recorded. Ultrasonically the horizontal section of the left eye was displayed on CRT and the recordings were analyzed on the base of movements of the crystalline lens and the optic disk. There was a small discrepancy of the amplitude between EOG and ultrasonography. In the imaginary target condition with eyes closed, both of the recordings by EOG and ultrasonography showed much larger amplitude than the real intertarget distance.

Many methods and instruments to record eye movements have been developed. To record movements of closed eyes, however, EOG seems to have been the only method. It is true that EOG precisely reflects real movements of open eyes, but the validity of EOG in the closed-eye state or when blinking has not been examined enough yet. In fact, some studies reported that the characteristics of eye movements while eyes were closed were different from those with eyes open (e.g. Lenox, Lange and Graham, 1970; Saito, Yamanobe, Katahira, Suda and Tsukahara, 1975). To approach this problem, it might be necessary to develop another method to record closed-eye movements.

In recent years ultrasonographs have been developed with clinical aims in medical science. Applying this, it might be possible to record closed-eye movements. Birnholz (1981) examined the development of human fetal eye movement patterns by projecting images of unborn babies ultrasonically. Naturally this method can be applied to fetal eye movements only. Is it possible to record eye movements by visualizing an eyeball itself ultrasonically? Since air inhibits the passage of the ultrasound beam, it is not as easy to create the image of an eyeball as it is to reproduce images of parts of the body such as the abdomen. But some ultrasonographs for the eye have been developed (e.g. Kaneko, 1979). And in clinical ophthalmology they are utilized for diagnosis of ocular tumours, retinodialysis, the presence of foreign matter in the eye, etc.; but not for recording eye movements.

In preliminary studies (Takeda, 1982, 1983) the simultaneous recording of eye movements was attempted by EOG and the ultrasonic method. Though the ultrasonographs were not for the eye, these studies suggest that the ultrasonograph is one of the possible instruments to record eye movements. Takeda and Tanaka (1983) illustrated that the visual axis could be estimated in the image of the eyeball displayed by the General ZD-252 ultrasonic device, an ultrasonograph for the eye. Figure 1 shows one of the obtained images.

On the ultrasonograph several points to be considered are as follows. B-scan ultrasonic apparatus is suitable for recording eye movements because the whole image of the eyeball can be presented only in a B-mode display. In order to display the change of tissue accompanying eye movements, it is necessary for the ultrasonograph to have high enough resolution to gain clear images and enough sampling time. Reflections of ultrasound occur when there are changes in tissue density. An image of a tissue can be displayed in the case when the ultrasonic

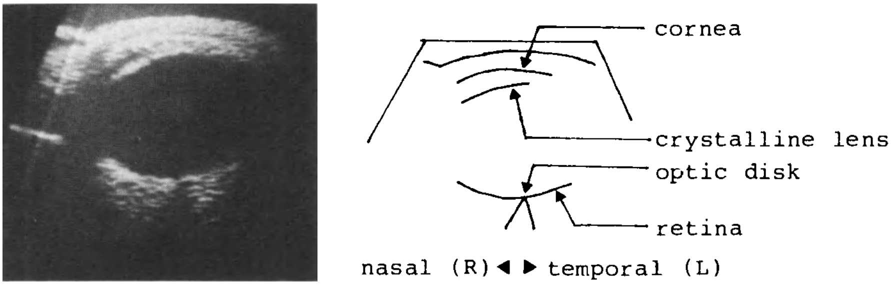

Figure 1 An eyeball displayed by General (Japan) ZD-252 ultrasonic diagnosis device. (Takeda and Tanaka, 1983)

beam and the tissue are subtended at an adequate angle. In general, high frequency of ultrasounds results in high resolution for shallow tissue, such as the eye. The sampling time depends on the scanning speed. Thus, the important characteristics of the ultrasonograph to record eye movements are (1) high frequency and (2) high scanning speed, if possible, in the B-scan.

In this paper two kinds of ultrasonographs were used to record eye movements and EOG was also used simultaneously.

EXPERIMENT 1

Method

The subjects were three male undergraduates (KY, IY, IM).

Eye movements were recorded by EOG and ultrasonography. A General ZD-252 ultrasonic diagnosis device (General, Japan) was used for the ultrasonograph. It was operated at 10MHz and its imaging rate was 0.91 frames per second. Its transducer needs a waterbath on the eye of the subject as Figure 2 shows. Each subject lay on his back with Ag-AgCl electrodes for EOG on his face. The left eye was visualized ultrasonically. To make a waterbath on the eye, an adhesive

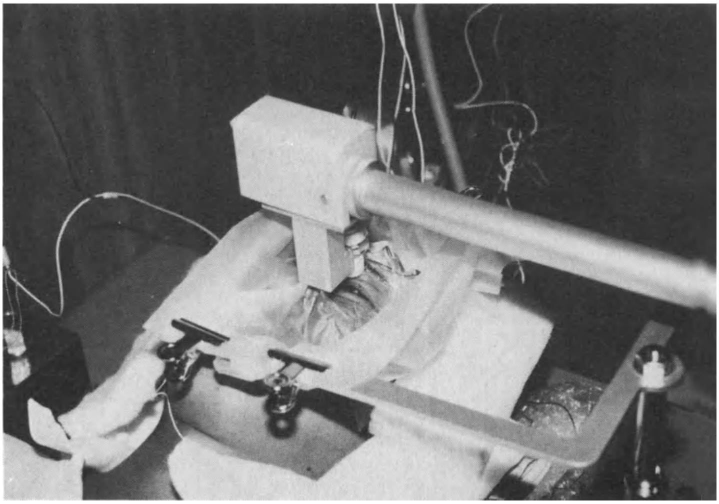

Figure 2 A subject with a waterbath on his left eye.

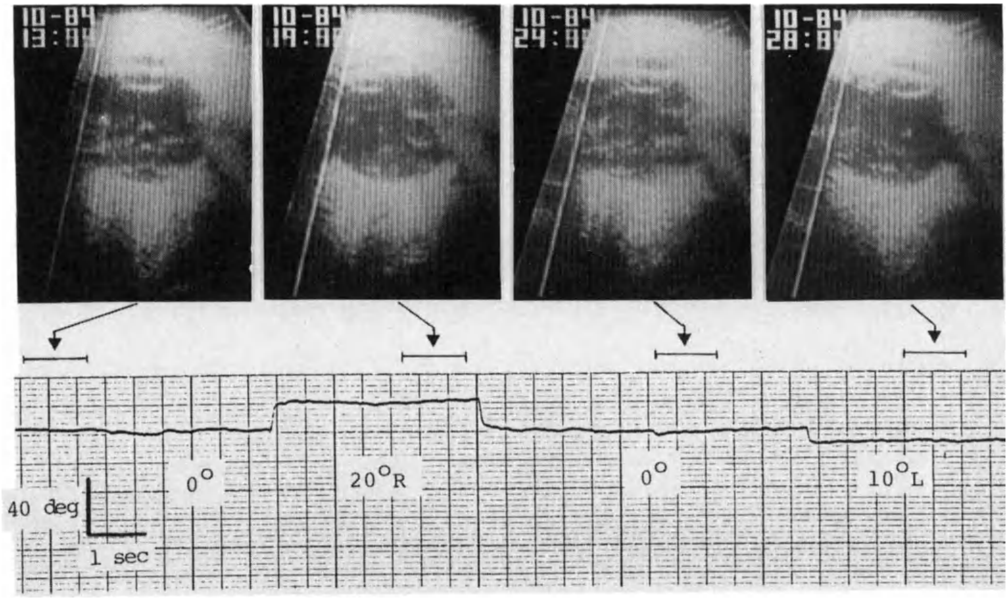

Figure 3 An example of simultaneous recording by EOG and ultrasonography in Experiment 1.

membrane with an eye-size hole was affixed around the left eye and a drape attached to it. The waterbath was filled with physiological saline solution and the transducer scanned it. The horizontal section of the eye was displayed in a B-scan mode on CRT and recorded on videotape. Target locations were 0°, 10°right, 20°right, 10°left and 20°left from the center of both eyes. Each target was a red 5mm-diameter LED. Each subject was instructed to gaze on the center and the eccentric target one after the other binocularly (with both eyes open) in the binocular condition and monocularly (with the left eye closed) in the monocular condition. Not all of the targets were examined because the waterbath obscured the view in some cases. The viewing distance was 50 cm.

Results

Since picture processing systems are not developed yet, still pictures, photographed from the video display for a single scan, were utilized for the analysis of the ultrasonographs. In the analysis the visual axis was estimated from the crystalline lens and the optic disk. As a result of the estimation, the center of the rotation was located at 13.0 - 13.5mm from the cornea. In the analysis of EOG the amplitude was based on the calibration with binocular vision without the waterbath. Figure 3 shows an example of simultaneous recording by EOG and ultrasonography.

The amount of data recorded was small. Both EOG and ultrasonography showed no significant differences between the monocular condition and the binocular condition in the amplitude, as Figure 4 shows.

There was a small discrepancy of the amplitude between EOG and ultrasonography. The mean amplitude of all the subjects' data combined is shown in Table 1. In general the amplitude recorded by ultrasonography was smaller than that of EOG and also smaller than the real intertarget angle. This discrepancy will be discussed later.

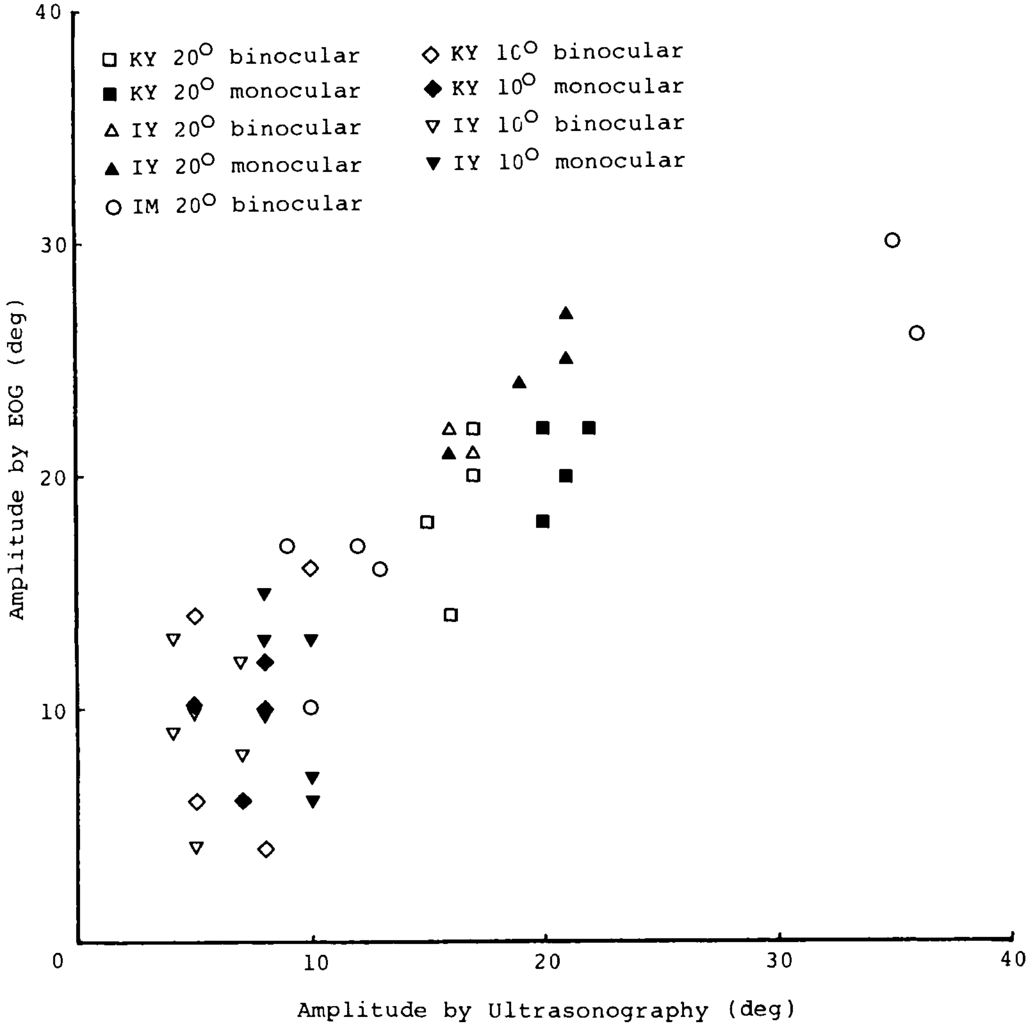

Figure 4 Amplitude of eye movements by EOG and ultrasonography. The movements of the left eye were recorded by the ultrasonograph (General ZD-252 ultrasonic diagnosis device).

Table 1 Mean Amplitude by EOG and Ultrasonography in Experiment 1.

(deg)

Condition	Intertarget angle	EOG	Ultrasonography
binocular	20 deg (n=12)	19.5	17.8
	10 deg (n=10)	9.6	6.0
monocular	20 deg (n= 8)	22.4	20.0
	10 deg (n=10)	10.2	8.2

EXPERIMENT 2

Method

The subjects were three male undergraduates (SK, MS, OH).

Eye movements were recorded by EOG and ultrasonography. Santesonic SSD-121 (Santen Pharmaceutical Co., Japan), a contact AB-scan ultrasonic apparatus for the eye, was used. It was operated at 7.5MHz, and its imaging rate was approximately 15 frames per second. The transducer was mechanically moved within a sector of about 40 degrees. Figure 5 shows the experimental situation. Each subject lay in the supine position with Ag-AgCl electrodes for EOG on his face. The left eye served as the subject eye in ultrasonography. The experimenter held the scanner in her hand and attached it in a stationary position to the eyelid of the subject. Scopysol was dropped on the eyelid to erradicate the air cavity between the scanner and the eyelid. The horizontal section of the eye was displayed in the AB-scan mode on CRT and recorded on videotape through the VTR terminal of the ultrasonograph. The targets were the same as in Experiment 1. For Subject OH, 5° left and 5° right targets were added to the initial range. In the actual target condition, the task was to gaze on the center and the 20° eccentric targets one after the other monocularly. After each subject observed the targets binocularly, he closed his eyes and moved his eyes imagining the targets in the imaginary target condition.

Results

Still pictures, photographed from the video display with a shutter speed of 1/15th second, were utilized for the analysis of the ultrasonography. In the analysis the visual axis was estimated from the crystalline lens which was clearly visible. The optic disk was considered in some cases. As a result of the estimation, the center of the rotation was located at 13.0 - 13.5 mm from the cornea. In the analysis of EOG the amplitude was based on the calibration with binocular vision. Figure 6 shows an example of recording by ultrasonography.

Figure 7 and Figure 8 show the amplitudes recorded by EOG and ultrasonography. In the imaginary target condition with eyes closed, both of the recordings by EOG and ultrasonography showed much larger amplitude than the real intertarget distance. This tendency was very remarkable, though a slight difference may occur

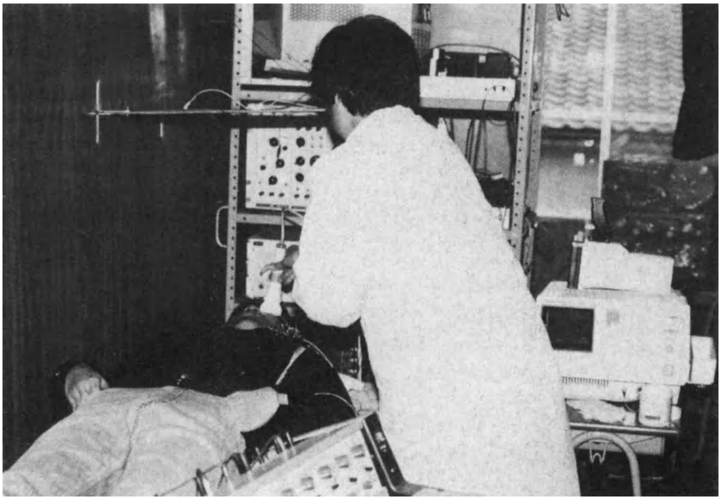

Figure 5 The experimental situation and the apparatus in Experiment 2.

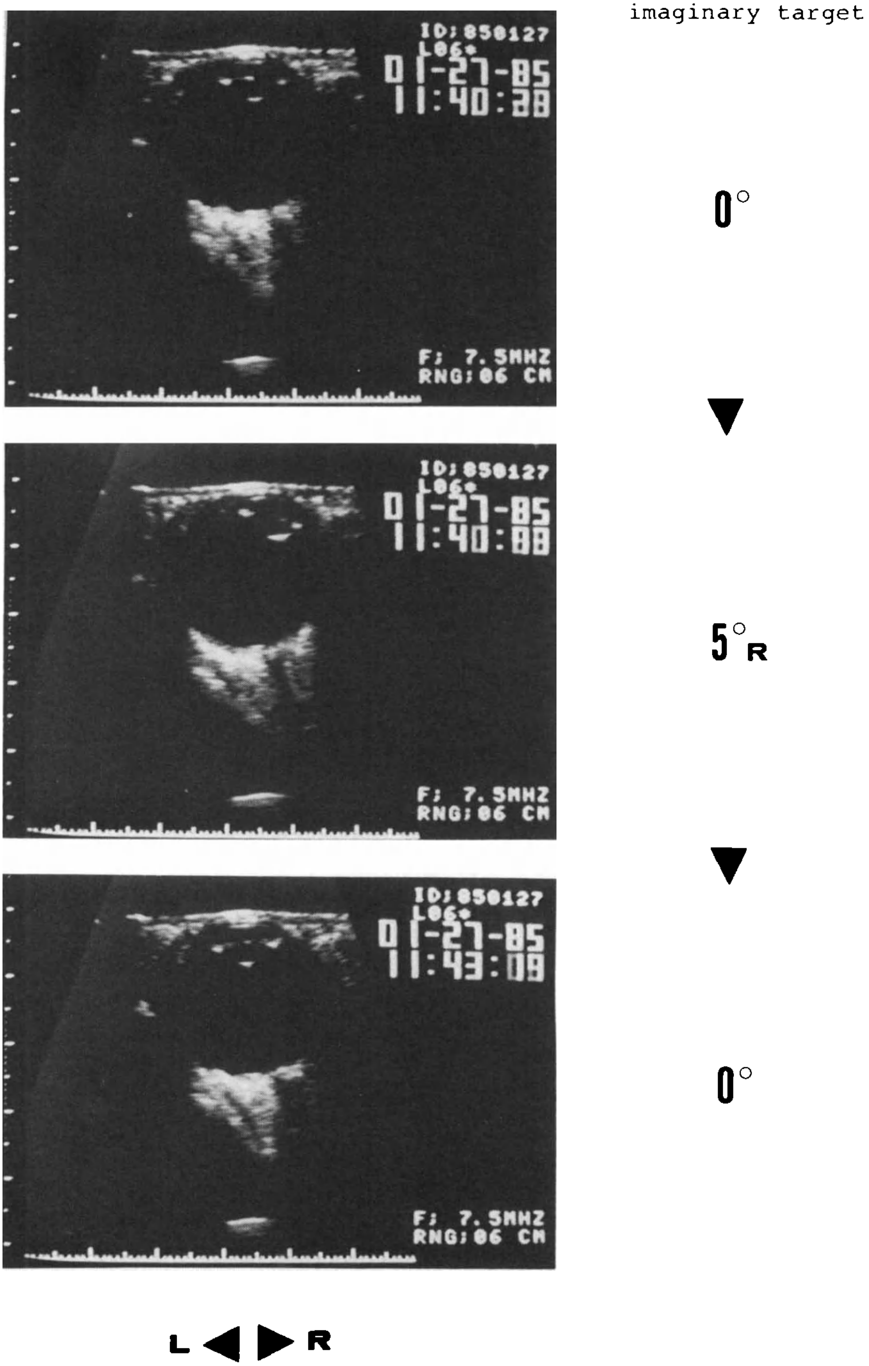

Figure 6 An example of recording by the ultrasonograph (Santesonic SSD-121) in Experiment 2.

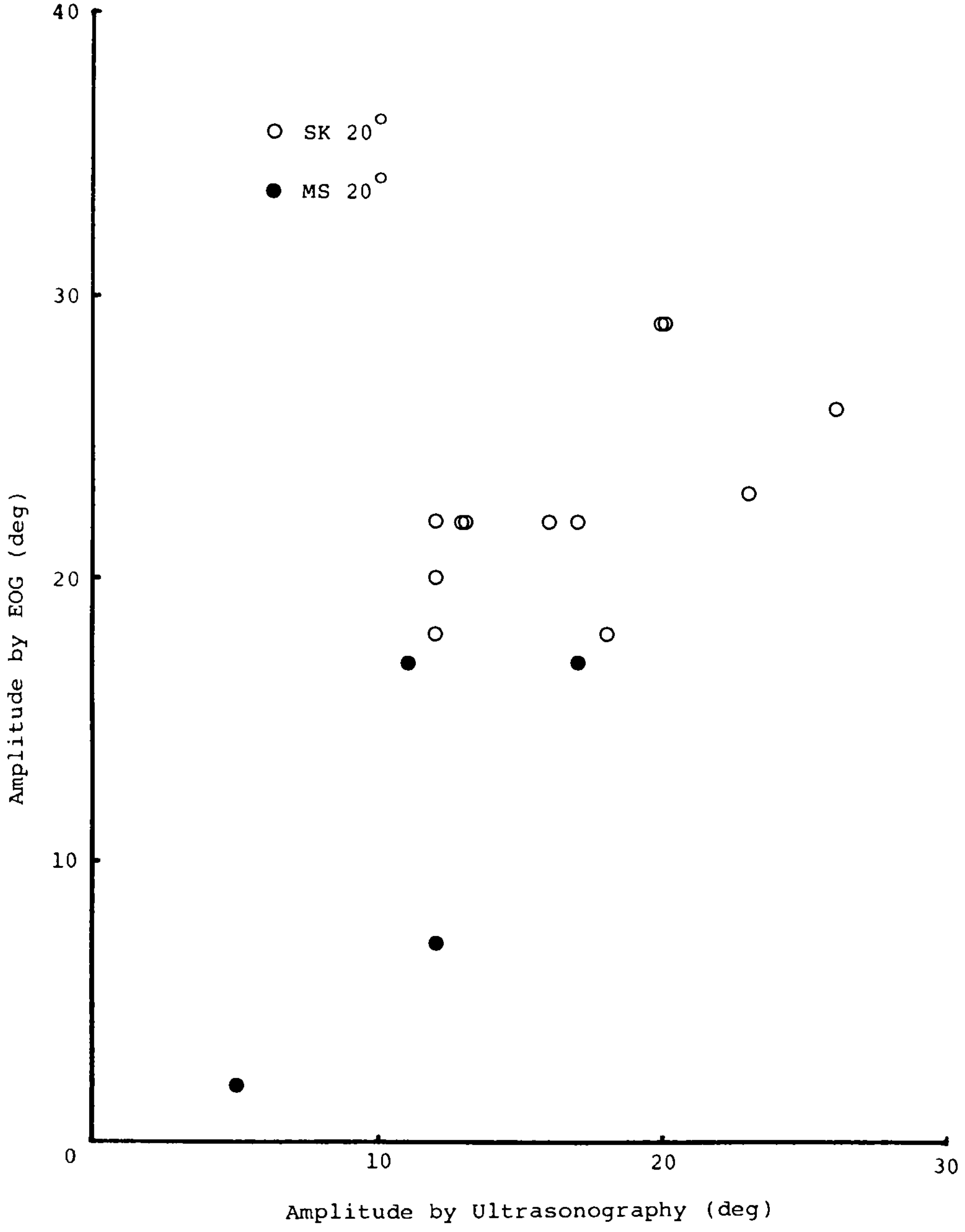

Figure 7 Amplitude of eye movements by EOG and ultrasonography in the actual target condition. The movements of the left eye were recorded by the ultrasonograph (Santesonic SSD-121).

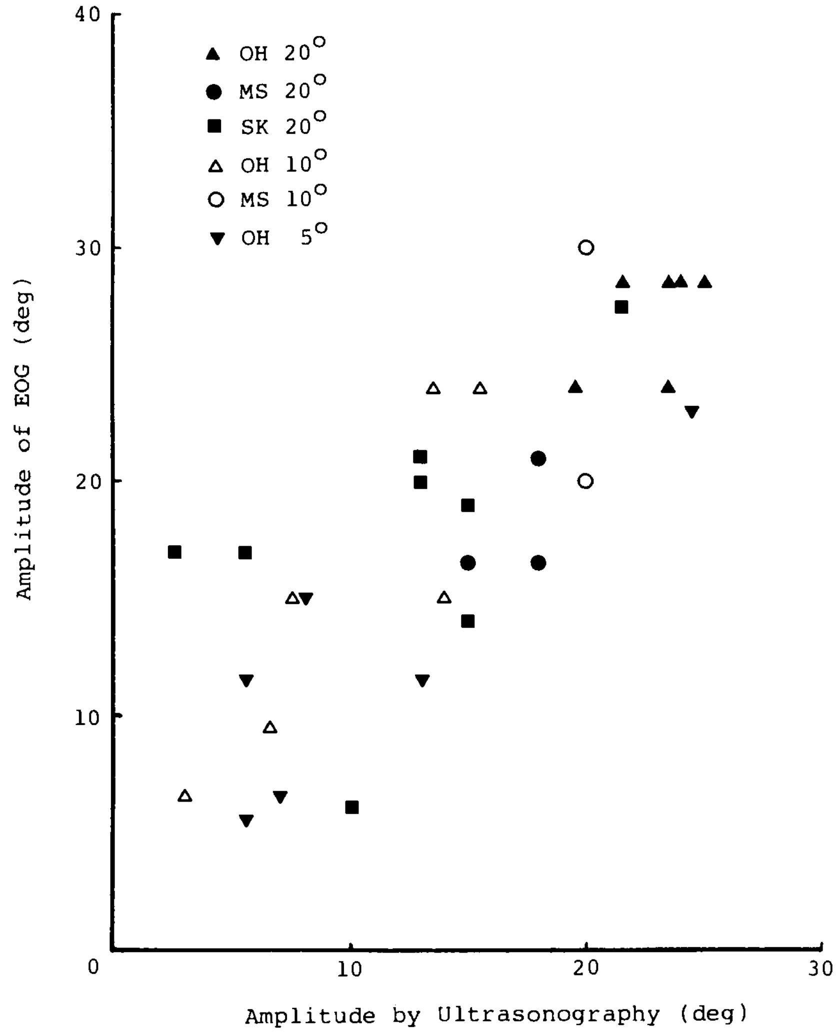

Figure 8 Amplitude of eye movements by EOG and ultrasonography in the imaginary target condition. The movements of the left eye were recorded by the ultrasonograph (Santesonic SSD-121).

in the numerical value in the results owing to sampling in the imaginary target condition because the eye was not stationary during imagery.

The discrepancy between EOG and ultrasonography was similar to Experiment 1.

GENERAL DISCUSSION

From the results of Experiment 1, it appears that the larger amplitude in the imaginary target condition is real and not an artifact of EOG. However, these experiments give no information on the cause of the overshoots that occur when the eyes are closed: the efferent signal or proprioception. Since Saito et al. (1975) reported that such overshoots did not occur in the dark with open eyes, the overshoots probably are not due to visual imagery.

As to the discrepancy between EOG and ultrasonography, it is dangerous to compare directly. The amplitude by EOG is that of both eyes and by ultrasonography that of only the left eye. An additional part of the discrepancy may be attributed to the slow scanning of the ultrasonograph in Experiment 1 and the problem of the holder in Experiment 2. Either or both may have produced a few errors. It is necessary to do further analysis with procedures that take vergence into account.

Some additional points should be noted concerning ultrasonic recording. Because the subject's eye is closed or in water, fine calibration is difficult. Thus, it is not easy to determine the accuracy of the ultrasonic method. nevertheless, the distortion of the pictures is probably within 1°, and the error in analysis of the pictures within about ± 2°. The development of picture processing system will reduce the error in the future. The positive characteristics of the ultrasonic method are as follows: (1) Closed-eye movements can be recorded, (2) artifacts are fewer, and (3) movements of any amplitude can be recorded. On the other hand, there are many disadvantages at the present time. A scanner can record either only horizontal or only vertical movements. Above all it is unnatural for the subjects to lay with a waterbath on their eyes. Furthermore, this method cannot be applied to long-term recording. There are problems in the position of the subject and presentation of stimuli. In the case of a contact scanner, a holder to keep the transducer on the eyelid and the surface of the transducer to fit into the eyelid are necessary.

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ON-LINE REGISTRATION OF EYE TRACKING MOVEMENTS IN THE A.C. MODE FOR THE COMPUTATION OF POSITIONAL DEVIATIONS

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This paper summarizes and discusses methodology and recent findings of a series of studies on eye tracking movements in psychotic patients, alcohol abusers and normals, studies employing alternating current (a.c.) amplification for the computation of positional deviations. An on-line system is described involving the use of an electronic pendulum, there being two different tasks, a less attention demanding (following a red light only) and a more attention demanding one (having to press a button each time the light changes to green). Eye tracking using a.c. amplification and a high-pass filter with a long time constant (corresponding to 0.16 Hz) is seen to provide excellent opportunities for the study of multilevel eye-tracking phenomena. A trial with the on-line equipment was designed for exploring, by means of spectography, what frequency components might be connected with the general findings, reported in earlier studies for macro-level tracking to be smoother under more attention demanding conditions and for microtremor rate to increase as cognitive strain increases. The frequency bands of the spectrogram comprising lower frequencies up to about 15-25 Hz were found to decrease in all subjects (n=6; all males, three of them health care personnel and three alcohol abusers) in the more attention demanding as compared to the less attention demanding condition, indicating tracking to be better during the former condition. At the same time higher-frequency bands generally increased during the more attention demanding condition as compared to the less attention demanding condition, the rise here occurring parallel to a corresponding rise in microtremor rate.

The potential difference which normally exists in the eye, such that the cornea is positive with respect to the retina, sets up a steady potential, which shifts with movements of the eye. By means of kinetic electrooculography, the potentials which ocular movements induce at skin electrodes placed around the eyes may be recorded. This requires the use of considerable amplification, since the potentials are only of the order of some tenths of microvolts (Shackel, 1976). Due to the particular periorbital distribution of the electrical field which is present, kinetic electrooculography seems to be the most suitable method for the recording of horizontal movements (Quéré et al., 1981). The recording of horizontal movements is generally performed through the placement of electrodes at the extreme canthi of the eyes, with a ground electrode being attached to the middle of the forehead.

Direct current (d.c.) amplification

The common electrooculographic method for measuring eye-tracking movements employs direct current (d.c.) amplification, a method in which the output signal, theoretically speaking, should correspond exactly with the input signal. In reality, however, such is not the case, the method having the major disadvantage that the presence of electrode drift causes an unstable baseline.

Alternating current (a.c.) amplification

With alternating current (a.c.) amplification, the output signal returns exponentially to the base line, even when the input signal is constant. The decay for this return depends on the value of the time constant selected, very short time constants of only tenths of seconds resulting in almost immediate return.

Within the field of electro-nystagmography, a.c. amplification has been employed for the study of the fast and slow phases of nystagmus through use of short as well as long time constants (Henriksson et al., 1972). It may be argued (op.cit.) that a.c. recording with a short time constant permits the velocity of the eyes but not eye position (degree of deviation) to be studied, whereas a.c. recording with a relatively long time constant (preferably 5 sec.) would avoid problems of d.c. drift and allow nystagmus beats of longer duration to be studied.

Developing the technique

The aim of the methodological work described here has been to develop an on-line recording technique for the investigation of deviant smooth-pursuit through use of electrooculography with a.c. amplification (Andersson, 1983, 1984a, 1984b, 1985). A.c. amplification was selected as the only acceptable alternative, since attempts to use d.c. amplification resulted in intolerably high baseline drift. Initial work in developing a suitable technique involved the constructing of an electronic pendulum for the exact control of stimulus position during tracking (Andersson, 1983).

Earlier versions of such a pendulum involved a 38.5 cm long string of 70 light diodes mounted in a straight line. Through each diode lighting successively for a brief interval, and the sequence of their lighting up reversing when the end of the string of diodes was reached, an illusion of continuous pendular-like movements was produced.

Although the movement displayed could be either of sinusoidal character or of constant speed, the latter type of stimulus was found to be the most discriminating, the majority of the experiments that were carried out using that type of pendulum. In addition, each light-diode could light up either red or green, which occasioned the use of an ABBA-type design for each of the subjects, the first and the fourth of the tracking segments to be analyzed involving red-light-only tasks, the second and the third involving a change of the light to green at short, irregular intervals. Each segment comprised slightly more than 30 secs. Subjects were to press a button each time the light changed to green, a green segment, when it occurred, comprising a one-quarter "swing" of the pendulum in the one direction or the other. In all the experiments, the subjects, who for the most part belonged to psychotic, alcohol abuser or normal groups, were seated 0.5 m from the pendulum, with their head movements being restrained by a chin support.

The first experiments in the series employed a mingographic preamplifier, which drove a Tandberg FM tape recorder. The preamplifier was RC-coupled to balance out d.c. voltage, most of these experiments using a high-pass filter with a time constant of 2.5 sec. Tape-recorded signals were digitized for each of the four slightly over 30-sec segments, such a segment comprising slightly more than 12 pendular cycles. Data-processing involved computing eye position (P) from electrical voltage (V) at each of the sampling points through solving the differential equation $dV/dt=a\cdot dP/dt-b\cdot V$, where dV/dt represents change in V over time. The validity of this measure is based on the assumption that the value of P is always the same for comparable points in any two cycles, and that the P values as a whole (which can be either positive or negative) have a mean value of 0. Each recording segment was shortened to exactly 12 cycles, a preliminary Fourier analysis being used in identifying cycles. A correction was employed for the existence of whatever small drift might (despite of a.c. amplification) be present, a correction which consisted of subtracting from V its mean value within each cycle. A more thoroughgoing Fourier analysis followed.

Measures employed in the first studies

In the first four studies (Andersson 1983, 1984a, 1984b, 1985), the following measures were obtained for each of the four periods:

(1) Noise/signal ratio: the ratio between the sum of the squared amplitudes of the 2nd to 6th harmonics, and the squared amplitude of the major wave (1st harmonic).

(2) 2nd to 6th harmonics, the ratio of the respective higher harmonic factor to the 1st harmonic factor. These values were related to the ideal values calculated for what would be perfect tracking.

(3) Deviation area: the area between the two curves describing the movements of the pendulum and of the subject's eyes, respectively, a low value indicating the subject to be following the pendulum closely.

(4) Microtremor rate: (d(tot)-d(eff))/d(eff), where d(tot) represents the total distance and d(eff) the "effective" distance the eye covered, and where d(tot) and d(eff) represent the sum of all small eye movements, as measured by recording eye position at 3.66 msec intervals, and at intervals nine times larger (33 msec), respectively.

Overall tracking performance (OTP); Dif-1; and Dif-2: For each measure above, a summary measure of the subject's overall tracking performance was calculated, as were two difference scores. Dif-1 indicates the effect of changing from the less attention demanding (red-light only) to the more attention demanding conditions (changing light color). Dif-2 represents the effect of practice.

Results of macrolevel and microtremor analysis

In the first study (Andersson, 1983) schizophrenics (n=13), cycloid psychotics (n=9) and normals (n=4) could be readily distinguished in terms of eye tracking performance. A cluster analysis together with criterion values for indicies based on various of the measures mentioned above yielded correct classifications in all but four cases. Patients' performance was found, for most measures, to be considerably better on the more attention-demanding than on the less attention-demanding task.

In the second study (Andersson 1984a) nineteen psychotic patients, most of these tested twice, provided cross-validational support for many of the previous findings. Both deviation area and noise/signal-ratio differentiated rather clearly between cycloid psychotics and schizophrenics. Cycloid psychotics, who could be expected on the basis of Leonhard's work (1957, 1979) to show phasic changes, seemed to show these on both noise/signal ratio and deviation area, the change on the latter measure suggesting improvement, the cycloid psychotics shifting between the first and the second testing (within a week) from being worse in performance than schizophrenics to not differing from them. Generally speaking, patients showed better performance under the more than under the less attention demanding conditions, as obvious from comparisons with the ideal tracking curve. The lone exception, here as in the earlier study, was in regard to the 5th harmonic. Inferior performance under the more attention demanding conditions there seemed to be reflective of the cognitive strain the complex conditions involved. Interestingly enough, microtremor rate was found to increase with an increase in cognitive strain, but to nevertheless decrease over time.

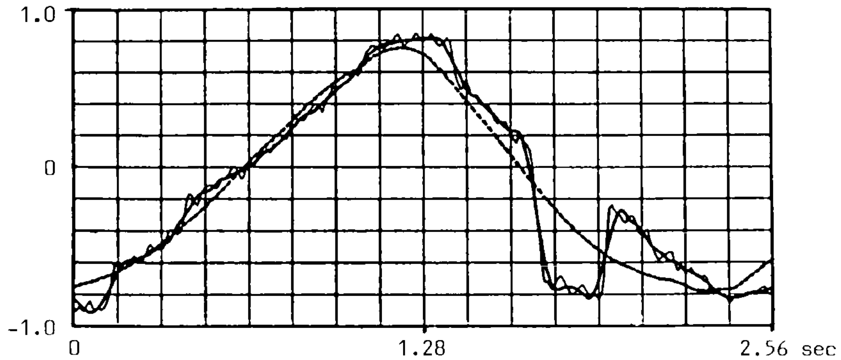

Figure 1. Eye-tracking segment (2.56 sec) from the record of a male alcohol abuser (age 34), illustrating the computation of eye position (lighter line), the V4-curve (darker line) and the V7-curve (dotted line). The presence of a macro-square wave in the latter part of the recording is evident.

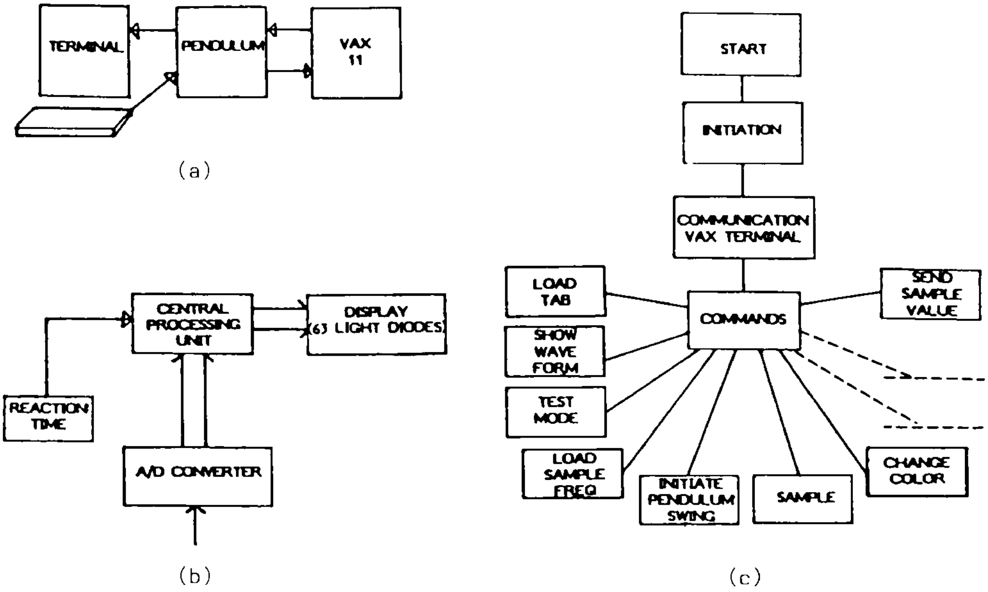

Figure 2. Schematic representation of the on-line eye-tracking system. The system works in transparent mode (a). Upon the occurrence of certain predetermined escape sequences the electronic pendulum reacts to certain commands (b). The program structure is illustrated in (c).

In the third and fourth studies (Andersson 1984b, 1985), 20 alcohol abusers were compared with the 19 psychiatric patients and the 4 normals already reported on. The results of repeated retests of 15 of the alcohol abusers during a three-month period were also examined. Although psychotic patients could not be distinguished from alcohol abusers on overall measures of noise/signal ratio and deviation area, microtremor rate was found to be categorically higher in psychotic patients than in alcohol abusers. This, together with certain other results suggested possible disturbances of a central nature in the psychotic patients.

In the original mingographic recordings a striking characteristic was found for the majority of alcohol abusers. This was the frequent occurrence of macro square-wave jerks in the same direction as that of the moving target, involving an initial saccadic deviation of at least 10 degrees amplitude from current tracking, followed (after a normal reaction time of about 200 msec) by a catch-up saccade in the direction opposite to the initial saccade. Such deviations were found to a significantly more frequent extent in alcohol abusers than in psychiatric patients.

A more extensive analysis of macrotremor

These findings suggested that a more extensive analysis of different types of deviations evident in the mingograph recordings might be promising (Andersson, 1985). Each individual record, comprising 12 periods of 12 waves each, was smoothed by computing sliding means over 16-point intervals, each such interval corresponding to 10 msec. Such a smoothed curve will be referred to as the V4 curve (Figure 1).

The V4 curve closely resembles the original curve, except for a certain obviously unconscious tremor, referred to here as macrotremor. Macrotremor was computed by counting upward or downward deviations of eye position from the V4 curve and then identifying bands of adjacent deviations. Analysis of jerks involved examining deviations of the V4 curve from the V7 curve, where the latter curve form was obtained by computing sliding and weighted means over 128-point intervals, the weighting utilizing the midpoint of a second degree regression (see Figure 1 for an illustration). As could theoretically be expected, this curve tends to coincide closely with the original stimulus movement. Deviations from this curve were identified. Changes sufficiently long and steep were classified as jerks. A jerk was at least double the speed of the stimulus, with the criterion for size being arbitrarily set at 0.15 of the maximum amplitude, i.e. 3.15 degrees.

A deviation that began and ended with a jerk was classified as a macro square-wave jerk if the line between the jerks was flat, horizontal, and of a certain minimum temporal size.

Cluster analyses based on macrotremor and V7-deviation, and on OTP, Dif-1 and Dif-2 scores (see above), applied to the recordings of a group of 14 subjects (seven normals, four psychotic out-care patients and three alcohol addicts, two of which were acutely intoxicated), succeeded quite well in distinguishing at the three-cluster level between the two acute alcohol abusers, the four psychotics and the seven normals, the sober alcohol abuser being found in the same cluster as the normals (Andersson, op.cit.). The results were seen as suggesting that the best approach to the analysis of eye movements is a multidimensional one which does not exclude the parallel use of both global and more specific measures.

Table 1A. Distribution of frequency components, 0-50 Hz.

Sums of amplitude values in the respective frequency intervals (0-5, 5-10, ... , 40-50 Hz). Microtremor rates (for computation, see text) are included for comparison. An increase in values under the more attention demanding conditions is indicated by underlining. N = normal subject, E = alcohol (ethanol) abuser.

Subject	Hz										Micro-tremor rate
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50	
N1:A	7.16	0.72	0.16	0.36	0.31	0.29	0.20	0.19	0.17	0.16	1.57
N1:B	6.71	0.67	0.56	0.36	0.43	0.35	0.26	0.28	0.33	0.28	3.76
N2:A	7.50	1.04	0.64	0.50	0.55	0.56	0.38	0.41	0.41	0.50	4.26
N2:B	8.08	0.87	0.52	0.44	0.45	0.71	0.63	0.47	0.44	0.55	4.93
N3:A	5.05	0.66	0.51	0.35	0.36	0.33	0.31	0.24	0.25	0.22	3.12
N3:B	3.92	0.53	0.39	0.33	0.36	0.33	0.39	0.29	0.29	0.26	3.88
E1:A	9.45	1.62	0.95	0.57	0.45	0.38	0.28	0.22	0.18	0.18	1.68
E1:B	8.61	1.12	0.75	0.53	0.45	0.43	0.35	0.30	0.26	0.26	2.58
E2:A	14.81	2.91	1.21	0.60	0.40	0.38	0.34	0.35	0.35	0.33	2.76
E2:B	8.07	1.58	0.94	0.63	0.45	0.45	0.40	0.37	0.33	0.34	3.42
E3:A	9.38	1.04	0.58	0.43	0.40	0.32	0.34	0.29	0.30	0.27	4.08
E3:B	6.57	0.64	0.43	0.38	0.35	0.31	0.32	0.28	0.25	0.29	3.97

B. Values of frequency components under (A) normalized.

First value (0-5 Hz) = 1000.

Subject	Hz									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
N1:A	1000	100	84	50	43	40	27	26	24	22
N1:B	1000	110	83	64	54	52	43	40	44	43
N2:A	1000	138	84	66	73	75	50	54	55	66
N2:B	1000	122	73	61	62	100	88	65	62	78
N3:A	1000	130	101	68	70	64	60	47	49	42
N3:B	1000	135	99	85	92	85	101	74	73	65
E1:A	1000	171	100	60	47	39	29	22	18	19
E1:B	1000	129	87	61	53	50	40	35	29	29
E2:A	1000	196	81	40	27	25	23	23	23	22
E2:B	1000	195	116	77	55	55	50	45	40	42
E3:A	1000	110	62	45	43	33	35	30	31	28
E3:B	1000	97	64	57	52	47	48	43	39	43

A trial with the on-line equipment

Following the experiments which were just described, an on-line system was constructed, one fully controlled by the central processing unit of a VAX 11 minicomputer (Figure 2). The system works in transparent mode; however, during certain predetermined escape sequences the pendulum reacts upon the occurrence of certain commands. Thus, for example, special commands may be used for loading the routines to be shown on the display, for determining the frequency of A/D sampling, for changing the stimulus color (to red or green), for measuring the reaction time to such changes, and for sending sample values from the pendulum to a buffer in the central unit which stores the values.

A high-pass filter with a relatively short time constant had been used in some of the earlier experiments, requiring major transformations of the original curve for the computation of eye position. Experience with using a high-pass filter with a longer time constant (corresponding to 0.16 Hz) had indicated that employing differential transformation for the computation of eye position resulted in only small or neglible changes. It was thus obvious that, since the lower frequency limit was 0.16 Hz, there was no need for using correction procedures, inasmuch as the stimulus cycle used was higher (0.33 Hz).

Method. An initial experiment employing this on-line equipment was performed, using a high-pass filter with the longer time constant (corresponding to 0.16 Hz). The experiment, comprising a small number of subjects, was designed to explore, by means of spectrography, what frequency components might be connected with the findings reported above concerning macro-level tracking being better under the more attention demanding conditions and of microtremor rate tending to increase as cognitive strain increases. Digital Fourier transforms of the input signal (using Hanning-window) were employed for analyzing the frequency components of records from a 30-sec red-light-only (less attention demanding) and a 30-sec red-and-green (more attention demanding) task. Microtremor rate was calculated using the measures described above.

Subjects. Six subjects were included in this study. All were males, three of them being health care personnel (subjects N1-N3, ages 41, 21 and 37, respectively) and three being alcohol abusers (subjects E1-E3, ages 39, 59 and 47, respectively), available at the primary care center during the period of testing. Of the alcohol abusers, subject E1 had stopped drinking the day before testing, after a period of heavy alcohol consumption, whereas subjects E2 and E3 reported they had been sober for the last three and nine months, respectively.

Results and Interpretation. The spectrographic analyses yielded results quite in agreement with those obtained earlier using the more complicated method for the computation of positional errors. The output at the lower frequency bands (up to 15 Hz) was found to decrease for all subjects under the more attention demanding as compared with the less attention demanding condition (Table 1A). This result corresponds with the earlier findings of tracking performance tending to improve generally under a more attention demanding condition. The normals tended to show values for the lower frequencies which were lower than those of the alcohol abusers, suggesting here as in the previous studies that tracking tends to be impaired in the latter group.

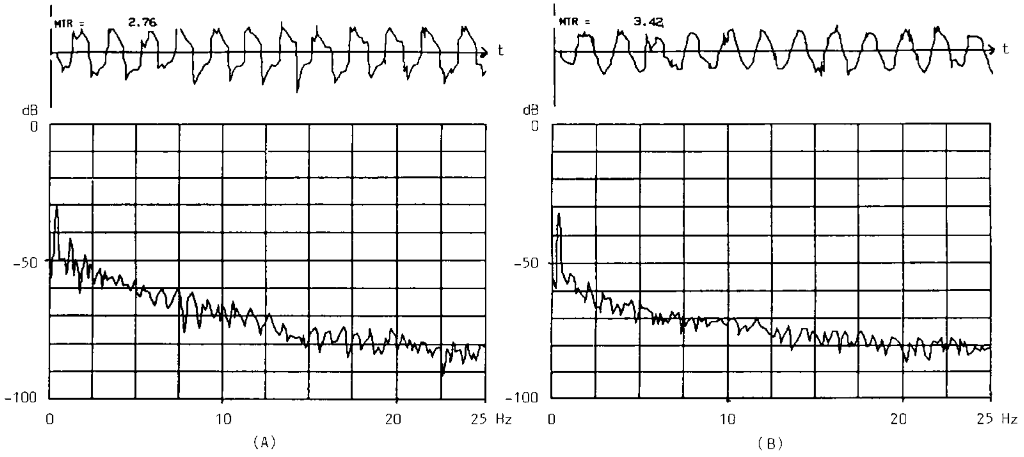

Figure 3. Upper half: 30-sec eye-tracking curves under less (A) and more (B) attention demanding conditions in an alcohol abuser (subject E2). Lower half: spectral analyses of the curves: x-axis 0 - 25 Hz; y-axis a logarithmic scale with 10 dB per division. Note the greater energy in the lower frequency bands (transition point at about 15 Hz) in (A) compared with (B). MTR = microtremor rate.

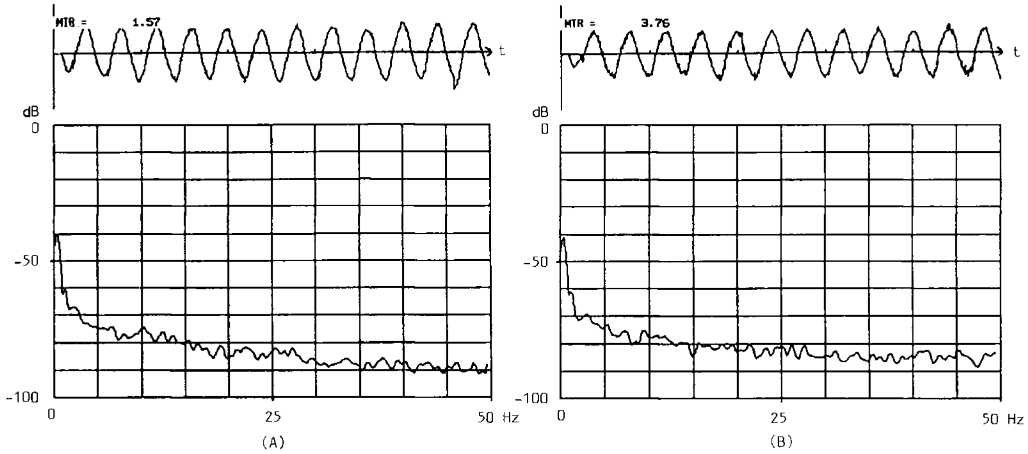

Figure 4. Upper half: 30-sec eye-tracking curves under less (A) and more (B) attention demanding conditions in a normal subject (subject N1). Lower half: spectral analysis of the curves: x-axis 0 - 50 Hz; y-axis a logarithmic scale with 10 dB per division. Note the greater energy in the higher frequency bands (transition point at about 20 Hz) in (B) compared with (A), and that differences between (A) and (B) are only slight in the lower frequency bands.

At the same time, microtremor rate increased generally in all three normal subjects under the more as compared with the less attention demanding condition. The rise of microtremor rate here occurred simultaneously with an increase in signals of higher frequency bands, i.e., from approximately 25 Hz to 50 Hz or higher, transition frequencies ranging from 15-30 Hz (Table 1A).

A similar increase both of higher frequency bands and of microtremor rate under the more attention demanding condition was also found in two of the three alcohol abusers (subjects E1 and E2). The third alcohol abuser (E3), however, was relatively high in microtremor rate under both the less and the more attention demanding conditions and tended to show a decrease in the frequency bands up to 45 Hz under the latter conditions.

As is evident in Table 1B, however, normalizing values for the frequency components through assigning the frequency band of 0-5 Hz a value of 1000 and expressing the values of the other frequency bands in terms proportional to this, nevertheless indicated a tendency for the relative energy within the higher frequency bands, those of 25-50 Hz, to increase under the more attention demanding conditions for all the six subjects.

Illustrations of the results of the spectral analyses of the recordings of two of the subjects (E2 and N1) are found in Figures 3 and 4.

Discussion. In sum, therefore, "on-line" eye tracking using a.c. amplification and a high-pass filter with a long time constant (corresponding to 0.16 Hz) is seen to provide excellent opportunities for studying multilevel eye-tracking phenomena. Spectrographic analyses and the normalization procedures which have been discussed may be useful for studying the frequency components involved in tracking. The normalization procedures which have been discussed would appear to offer considerable potential for the microtremor phenomenon. Information obtained through spectrographic analyses, however, does not seem to succeed in distinguishing between various types of macro-level deviations. Thus, various other types of measures are needed for such purposes (see Andersson, 1985, for a description of certain measures of this sort which could be included in an on-line analysis).

The existence of both higher and lower level trajectory controls, which may influence each other mutually, might serve to explain some of the findings concerning macro- and micro-level tracking reported in a series of studies by the present author (Andersson, 1983, 1984a, 1984b, 1985). It can be hypothesized that microtremor tends to function together with microsaccades and ocular drift in lower level trajectory control. If this lower level of control cannot be optimized because of limitations in information processing capacity, higher levels of control may be involved, the solutions thus attempted resulting in suboptimal trajectories. The study of adaptive resources at both lower and higher levels may shed light upon the much discussed question of whether the saccadic and smooth tracking systems are independent, and may suggest that an interaction of velocity and positional information takes place, not only at higher and lower levels but also between such levels. One inter-level link may be saccadic suppression (cf. Zuber and Stark, 1966), which it can be suggested may influence activity at higher and lower levels differently.

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EYE MOVEMENTS: From Physiology to Cognition
J.K. O'Regan and A. Lévy-Schoen (editors)

An Eye Motion Dependent Interactive Display

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Using readily available equipment, we assembled a digital graphics system to investigate several facets of how the human visual system gathers information. Of particular interest is the relationship and interaction between central and peripheral visual processes, investigated by selectively prohibiting foveal or peripheral visual access to pertinent details in a display. This process requires realtime display modification in response to eye movements and is accomplished by utilizing the capabilities of a graphics array processor to manipulate the 512x512x8 bit images at TV line rates. An infra-red limbus reflection technique is used to track the observer's gaze. Our applications involved radiologists looking at x-ray images of the human chest. We describe both hardware and software aspects of our interactive visual display system and mention its applications in our laboratory.

INTRODUCTION

The field of radiology is one that relies primarily on visual information gathering. Interpreting variations in images of the body displayed on a sheet of film or on a video monitor is a large part of the radiologist's task. Interpretation, however, is usually preceded by a visual search for abnormal or suspicious shadows. One of the more interesting and fruitful endeavors in the study of image interpretation by radiologists has involved the use of eye motion monitoring equipment and radiologists. It is well documented that radiologists do not routinely conduct exhaustive searches of an entire image, but tend to spend a disproportionate amount of time either on those areas that are suspicious based on the patient's symptoms and history, or on distinctive features that attract the radiologists attention (Lewellyn (1969)). This practice occurs despite being taught to use an exhaustive search technique (Carmody, Kundel and Toto (1984)). We developed an eye motion contingent display system, limiting foveal or peripheral visual access to selected displayed details, with the hope of gaining insight into scanning behavior (Nodine and Kundel (this Volume)). This paper gives an overview of some hardware and software aspects of an eye motion contingent display.

We developed the interactive display system to allow us to present different pictorial displays to the central and peripheral fields of vision, even while eye movements are taking place. This required the capabilities of a graphics array processor to manipulate the 512x512x8 bits images with sufficient speed to track the position of the axis of the gaze. Since the observers are free to search an entire display area, it is necessary to interactively follow the gaze of the observer's eye such that the foveal and peripheral fields of vision are tracked by respectively designated images on the display console.

The basis of the system is a circular window of a specified size that follows the gaze of the observer. The border of the window defines the border between one image and a second image. The visibility of the window depends on the difference between the image displayed inside and outside the window (figure 1). In a recent set of experiments (Kundel, Nodine and Toto (1984)), the images were identical radiographs of the chest except for the presence of a solitary nodule in either the central or peripheral field of vision. Nodules were synthesized using a program written expressly for producing lesions with user defined characteristics.

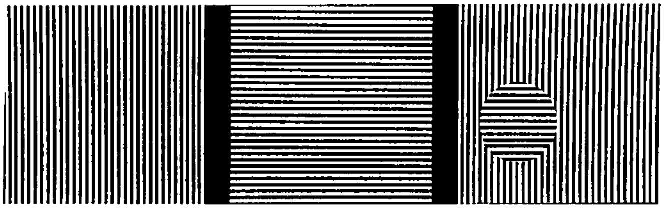
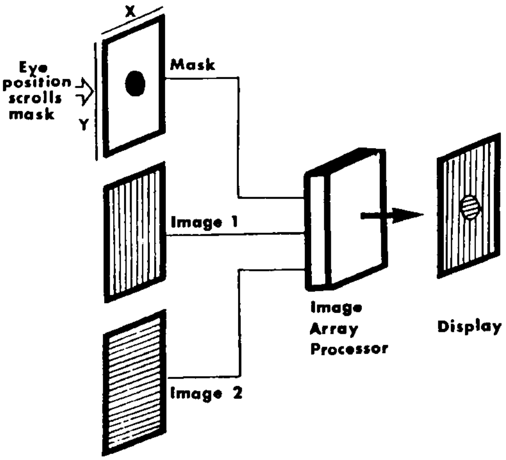


Image 1 Image 2 Composite Image

figure 1

GENERAL HARDWARE OVERVIEW

The eye movements of observers were monitored with a Biometrics Eye Movement Monitor Model 200-1. The eyetrack monitor consists of two parts: a pair of spectacles(half-frames without glass) which act as a mount for infra-red emitters and detectors, and a control console with the required power supplies, amplifiers, gain and offset controls, etc. The monitor system senses the vertical excursions of one eye and horizontal excursions of the opposite eye by reflecting an invisible, pulsed, low intensity infra-red light off each eye. The reflected light from each eye is converted to a voltage and sent through an A/D (analog to digital) converter for processing by the microcomputer. The manufacturer claims a spatial resolution of "a few minutes of arc" ...."with a rigid head restraint." The 8-bit 2-channel A/D converter circuit in our eyetrack monitor was designed and built in our laboratory, but the eyetrack monitor is available with an optional 8-bit A/D converter from the manufacturer.



System Schematic Diagram

figure 2

The graphics capability is provided by a Gould DeAnza IP6400 Image Array Processor, which is a raster display device that allows us to display gray-level images that are pertinent to the radiologist, such as x-ray images of the chest. The images are 512 x 512 pixels square (.25 Mbytes) and each pixel can be assigned an intensity value of 0-255. The graphics system is set up to acquire, store, manipulate and display 4 separate 512 x 512 gray level images. Further details about the graphics system can be found in PROCEDURE.

The video display system is packaged around a Digital Equipment Corporation 11/23 microprocessor with 128 kbytes of RAM storage, a 40 Mbyte Winchester disk drive and a 500 Kbyte floppy disk drive. The LSI-11 based microprocessor is a 16 bit machine with a clock rate of 10.5 MHz. The microprocessor was programmed in Fortran and Macro-assembly. A large capacity, rapid access mass storage device, such as the Winchester drive, is essential for the storage and rapid retrieval of the many images that we required in our work. Image retrieval from the Winchester was quiet and fast, less than 2 seconds for .25 Mbytes of image data. The noise level of an operating disk drive unit was a factor in our study, minimizing the audible distractions to the observers, since all equipment was in the same room as the observer.

Since our experiments require that we display images that were originally recorded on film, the IP6400 is connected to a Sierra Scientific video camera (Model LS2P-16) which we use to transform images from x-ray films into the IP6400 display memory planes and then into disk storage for retrieval on demand. The video camera is an essential part of our system because of the nature of our image database, but could be eliminated if displays were to be software generated.

PROCEDURE

A trial consists of three phases: pre-viewing calibration, image viewing, and post-viewing calibration. The required display images and patterns are loaded into memory prior to the start of a trial. At the appropriate times, the images in the various memory planes are directed to the TV display consoles.

Two TV display consoles were used during the experiments. One 17 inch diagonal TV monitor was viewed by the observer participating in the experiment and a second TV monitor was used by the experimenter to follow the calibration and the progress of the experiment.

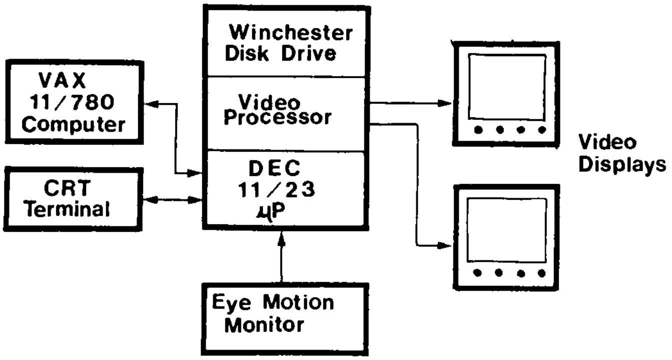
The data collection was designed to be as simple and quick as possible while still retaining accuracy and reliability. Even though the eye position sensors worn by the subject are carefully adjusted, some channel (vert./hor.) crosstalk and nonlinearities may persist. A data correction routine is therefore used to correlate spatially the x,y coordinate data with the rectilinear display. This is accomplished by having the observer view the 3 X 3 dot pattern, sequentially fixating each dot and pushing a button to inform the computer when the dot is being fixated. The spatial calibration procedure typically takes about 5-10 seconds. Two second degree polynomial equations are then computed to correct the x,y coordinates. This requires about 0.5 seconds of processing time. The correlation of the observer's corrected calibration pattern to the displayed calibration pattern is usually accurate to within 1 degree of arc as subtended by the observer's eye over the whole field of view. Data is considered acceptable if the position of gaze can be known within 1 degree with reasonable confidence.

Following the calibration process, the observer sees the appropriate chest display for up to 20 seconds. The observer can terminate a trial early by pressing a button.

After the data collection period is over, the test image is replaced by a 5-point post-viewing calibration pattern which we compare to the 9 point pre-viewing calibration to determine if head movement occurred during the trial. Head movements are detected only if the head is in a different position at the time of post-viewing calibration than at the pre-viewing calibration period.

SOFTWARE

All program software is written in Fortran IV, except for several utility routines which were written in Macro assembly. The key to the gaze-following technique is in the DeAnza's special display mode called "composite overlay". This display mode allows the user to display on the observer's TV monitor selected pixels from any of the memory channels in the IP6400 (figure 3). The 4-bit overlay channel is set up in a 512x512 pixel format to map to the display channels pixel by pixel. One might think of each pixel in the overlay channel as a four-position switch, choosing which memory channel will be sent to the observers' monitor for each of the 512^2 pixels in the display. Once the windowing map is created in the overlay channel, the position of gaze data can be used to scroll the overlay channel, modifying the display such that the central field of vision is tracked by the center of the window. Using this facility, we can limit what visual information is presented to the central and peripheral fields of vision by loading the display channels with appropriate data.



Schematic of Overlay and Image Channels

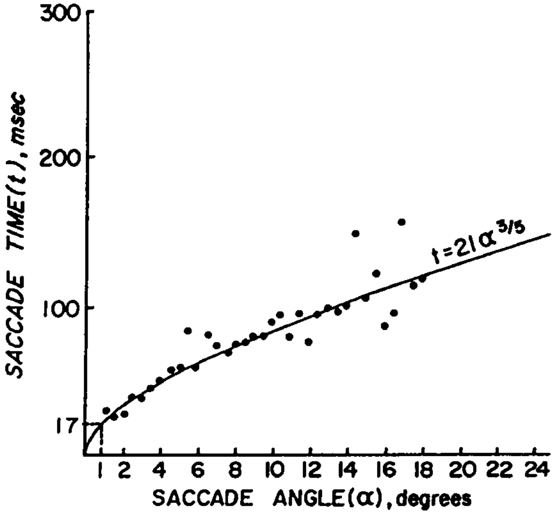
figure 3

The gaze following technique used does not require us to determine when the onset of a saccade occurs. Instead, the image is updated based on the most recent known position of the gaze. The spatial calibration equations are inserted in the data collection loop of the program for on-the-fly correction.

Fixations are investigated at our leisure after data collection has concluded. This avoids the use of excessive processing and resultant system delays during the data collection period.

LIMITATIONS OF INTERACTIVE SYSTEM

One of the limiting factors in a system such as this is the ability to modify the image in the time of a relatively short saccade. McConkie reports that saccades can be as short as 20 msec. when the task is to read printed text (McConkie, Wolverton and Zola (1984)). Carpenter reports that " ...the duration of saccades larger than 5^o in amplitude is roughly given by 20-30 msec plus 2 msec for every degree of amplitude" (Yarbus (1967)). Yarbus gives an empirical formula: T (sec) = 21 x Alpha$^{(2/5)}$. We analyzed the eye position data, consisting of over 2500 fixations, of observers searching for nodules in normal chest images (no nodules present) and found that the relationship of saccade duration vs. saccade angle was similar to Yarbus' empirical description, but with a slightly steeper slope: T (sec) = 21 x Alpha$^{(3/5)}$. (figure 4)

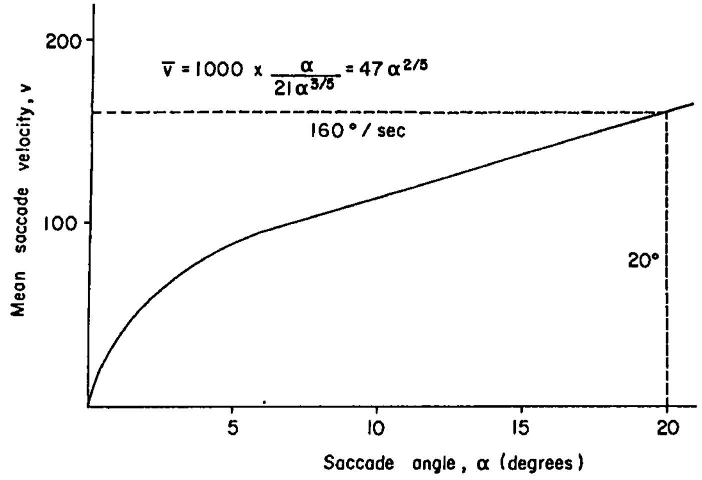


Graphs of Saccade Duration vs. Saccade Angle

figure 4

The rate at which we can update the displayed image is limited by the retrace rate of US standard 525 line TV monitors (60 fields/sec), thus our display gets refreshed and updated every 16 msec. We synchronize our data collection rate to the field retrace rate of the TV monitors, collecting 60 coordinate pairs/second (16 msec. intervals). Our data indicate that saccade angles associated with saccade durations of 16 msec. or less are generally less than 1 degree. Micro-saccades and high frequency tremors occur faster than the system can respond. Since we are attempting to track the position of gaze with a system that has a finite response time, we use a window of a large enough size to provide a zone of indeterminance. Thus, the shortest saccades fall within the same zone covered by the previous position. It should be emphasized that the coordinates of the window center are not based on fixations, which would require processor time to calculate, but on the most recent coordinate pair. Each coordinate pair is the average of 12 samples within each 16 msec. interval.

The refresh rate and window size determine the maximum angular velocity that can be tracked by the system. Computations of mean angular velocity were derived from the equation of saccade duration vs. saccade angle, which fit our data rather well (figure 5). However, the instantaneous velocity is the parameter that will limit the tracking during a saccade and the peak instantaneous velocity may exceed the average velocity by a factor of two or three (Yarbus (1967)). There is evidence that perception is interrupted for the brief period that the saccade is occurring (Shakhnovich (1977). Tracking during the longer and faster saccades may not be precise, but the misregistration is not reported by the observer even when the window is very visible.



Graph of Mean Saccade Velocity vs. Saccade Angle

figure 5

We have used various window sizes in our experiments, but the most interesting are in the range of 3.5 to 5 degrees in diameter. The maximum angular velocity that we can track is 160 degrees/sec. while still coupling a window of diameter 3.5 degrees to the position of gaze. This corresponds to a saccade angle in excess of 20 degrees. Our observer display was 25 cm. square, which at 70 cm. from the observer's eyes is about 20 degrees on a side. Our data demonstrates a modal saccade angle of 3 degrees and a mean of 5 degrees, with 97% of the saccade angles being less than 15 degrees.

Since a field comprises half of a TV frame (interlaced), any radical movements away from the window tend to split the differences between the two images being viewed, but this is not perceived by the observer.

CONCLUSION

Because of the nature of our display hardware and the powerful array processor facilities, minimum preprocessing of the streamed position data is necessary before modifying the display. Preprocessing consists of high-frequency noise filtering and spatial correction of the data prior to updating the display. There is no need to determine when a saccade begins or to project the location of the next fixation as necessitated by other systems. Coupling the window to the points of fixation is accomplished with reasonable accuracy and reliability.

The problem of blinks, however, has not been solved. A blink filter requires additional preprocessing of the data and would cause a degrading of the system response time. We ask the observer to refrain from blinking for the data collection period (typically 10-20 seconds) as much as possible in an attempt to minimize blink associated tracking.

This contingent display system is not specific to the radiology setting, but may be useful to those studying the perception of art, text, or any information that can be displayed on a TV monitor using grey levels. Factors such as choice of host processor, sophistication of the graphics hardware, display devices, mass storage devices, etc. vary in capability and cost. The display system that we developed cost approximately $85,000 (US) in 1981, but is used as a general laboratory tool for graphics work needed in several lines of reseach performed in our lab. The cost of hardware of similar capability today (1985) would cost somewhat less.

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A NON INVASIVE INSTRUMENT FOR EYE ORIENTATION MEASUREMENTS IN NATURAL ENVIRONMENTS.

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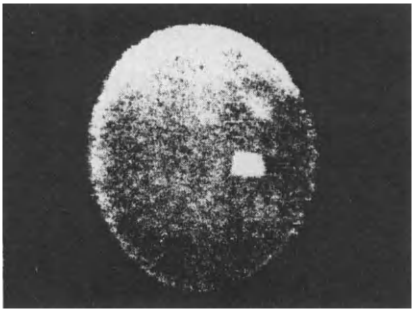
INTRODUCTION

Original techniques for real time pattern recognition and feature analysis from standard video signals have been applied to the monitoring of eye movements and pupillary size during visual field and electrophysiological examinations in routine ophthalmological practice. The basic features of the reaulting instrument are :

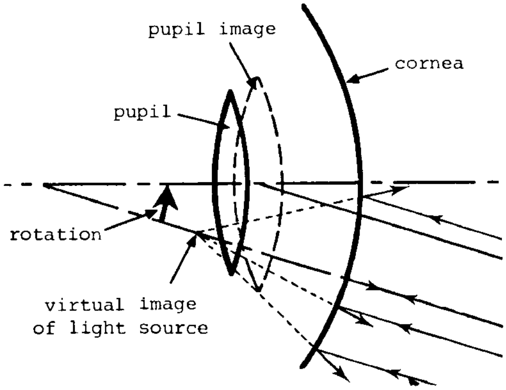
- the use of low-cost hardware, i.e. standard video and LSI circuitry ;
- the measurement of eye orientation from the position of the corneal reflection relative to the bright pupil ;
- real time processing and high data throughput of 50 samples per second, allowing pupillary and oculomotor reflex analysis ;
- specialized hardware and software permitting both adjustment-free feature identification and analysis directly from the video signal.

BACKGROUND

The eye of the patient is illuminated with near i.r. radiation. Part of the incident light beam is reflected by the cornea and produces the so-called corneal reflection. The transmitted rays are reflected back from the retina and back light the pupil (bright pupil effect). The eye orientation is determined from the relative position of the corneal reflection with respect to the bright pupil image.



Video image of bright pupil and corneal reflection

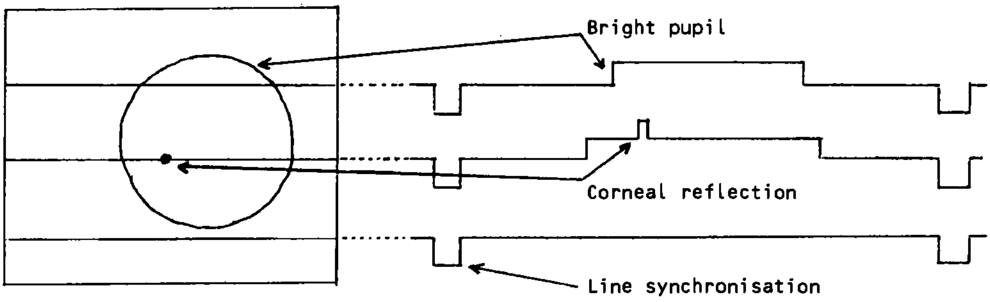


The origin of the bright pupil and corneal reflection

SELCTIVE DETECTION

The video signal is analysed in real time by a shape detector circuit to detect selectively the beginning and the end of the pupil and the corneal reflection on each video line. Using shape detection instead of amplitude level or amplitude variation detection improves performance significantly with low contrast images. It eliminates the problems associated with variations of the detection thresholds with pupil size fluctuations.

A preprocessing interface determines for each line the coordinates of the pupil boundary as well as the corneal reflection and transmits this information to the microprocessor memory.



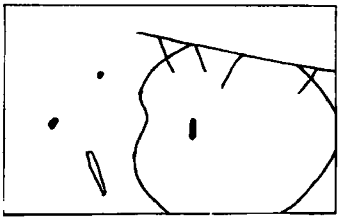
Video signal produced by the camera

IMAGE ANALYSIS

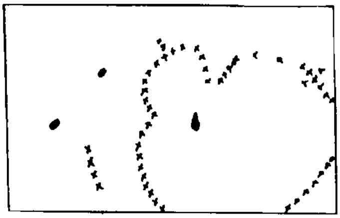
The image processing is carried out by a microprocessor in 20 ms and gives directly the pupil center and corneal reflection positions. These data are transmitted for further processing: fixation monitoring, pupil analysis or eye orientation measurements.

The pupil boundary is identified by several algorithms making use of contour continuity and curvature consistency. These methods eliminate the data resulting from detection of parasites and eyelashes.

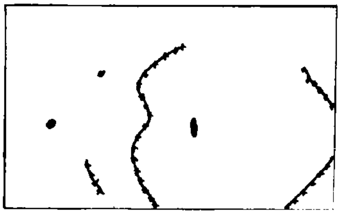
A specific algorithm computes the pupil center and the pupil radius from points chosen along the selected boundary. The precision of pupil center position is 0.05 mm with a 15 x 15 mm^2 image area at the eye even if the eyelashes mask a large part of the boundary.



Sample video image with eyelashes and parasitic reflections



Pupil boundary and corneal reflection detection



Data chain extraction based on contour continuity

Data chain extraction based on curvature consistency

CONCLUSION

The entire image analysis is performed within 15 ms. A few ms are left for complementary programs such as eye orientation or pupil surface area calculation. Protocols for automated focusing and fast 5 point calibration are also provided. Sampling frequency of eye orientation depends upon the image complexity. 50 Hz are obtained in an ideal situation but this result decreases down to 25 Hz when many artefacts are present. Measurements of eye orientation are performed with a resolution of 0.25 degrees and an accuracy of ± 1 degree for the central 40 degrees.

LIGHT SCANNING OPHTALMOSCOPE

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CONVENTIONAL OPHTHALMOSCOPES

TWO INSTRUMENTAL PUPILS ↳ DILATATION OF EYE PUPIL (MYDRIATICUM)
PHOTOGRAPHIES OF OCULAR FUNDUS : 3 OR 4 IMAGES / SEC.

PRINCIPLE OF SCANNING LASER OPHTHALMOSCOPE

THE 2-D DEFLEXION OF A LASER BEAM OBTAINED BY MEANS OF A SCANNING DEVICE PERMITS TO EXAMINE THE RETINA POINT BY POINT .

- INSTANTANEOUS RETINAL FIELD ≈ NULL .
- FLYING SPOT : SEQUENTIAL ILLUMINATION OF EVERY POINT ON THE RETINA $\Delta T = 1/10^7$ SEC.
- POWER DENSITY LOWER THAN FROM GIVEN BY A CONVENTIONAL OPHTHALMOSCOPE .
- MAXIMUM SCANNING FIELD OF OUR SET-UP : 20° X 12° .
- RETINAL IMAGE OBTAINED POINT BY POINT ON A STANDARD TV MONITOR (25 IM./SEC.) .
- POSSIBILITIES . VIDEO TAPE RECORDING , REAL TIME IMAGE PROCESSING .

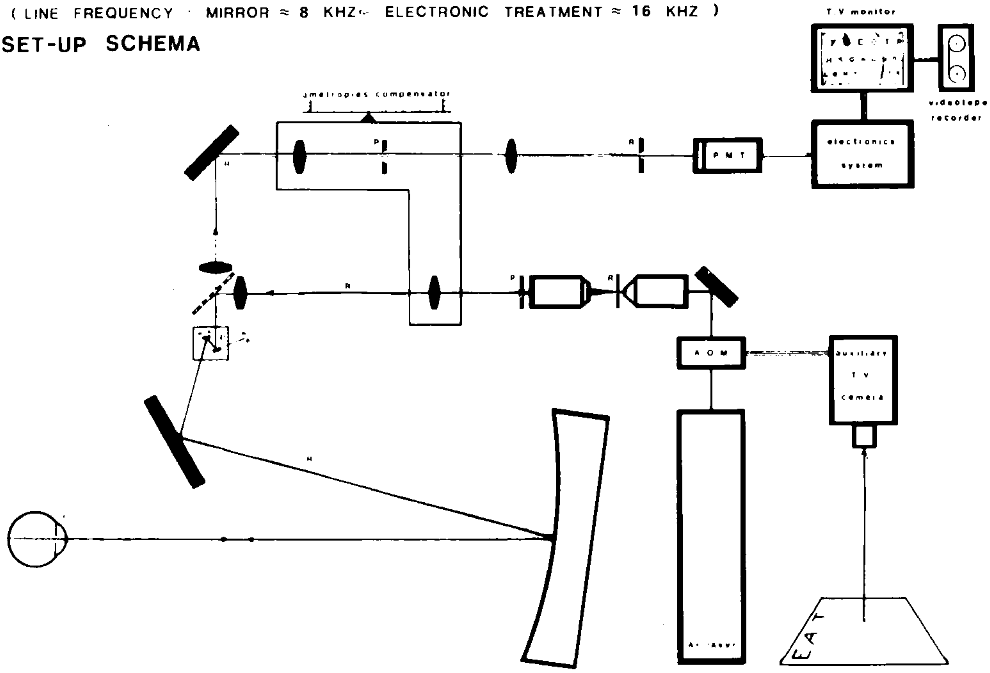
DOUBLE CROSS SCANNING DEVICE ↳ ILLUMINATION / OBSERVATION BEAM .

- STABILIZATION OF THE IMAGE OF THE RETINAL FLYING SPOT ↳ ELIMINATION OF STRAY LIGHT WITH A DIAPHRAGM .
- ONE AND THE SAME INSTRUMENTAL PUPIL : NATURAL PUPIL OF THE EYE .

SCANNING DEVICE TECHNOLOGY

TWO ORTHOGONAL SCANNING MIRRORS (RASTER FREQUENCY : 50 HZ)
(LINE FREQUENCY · MIRROR ≈ 8 KHZ ↳ ELECTRONIC TREATMENT ≈ 16 KHZ)

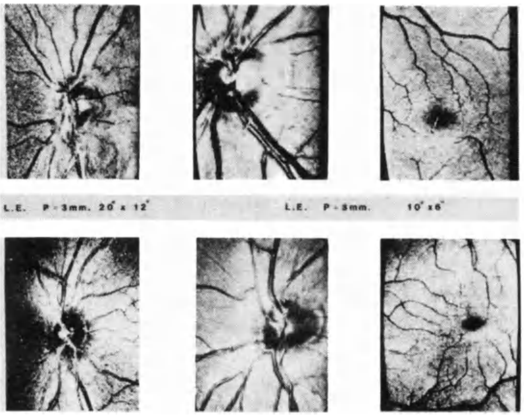
SET-UP SCHEMA



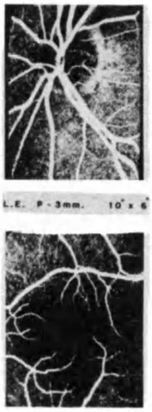
OPHTHALMOSCOPY PURPOSE

OBSERVATION OF OCULAR FUNDUS (MACULA ,PAPILLA , PERIPHERAL RETINA)
DETECTION OF RETINAL DISEASES
STATIC EXAMINATION (DETACHMENT OF RETINA , MORPHOLOGY OF PAPILLA , NEOVASCULARIZATIONS ...)
DYNAMIC EXAMINATION BY FLUORESCEIN ANGIOGRAPHY (VEIN OCCLUSION , BLOOD RETINAL BARRIER ...)

OPHTHALMOLOGICAL APPLICATIONS



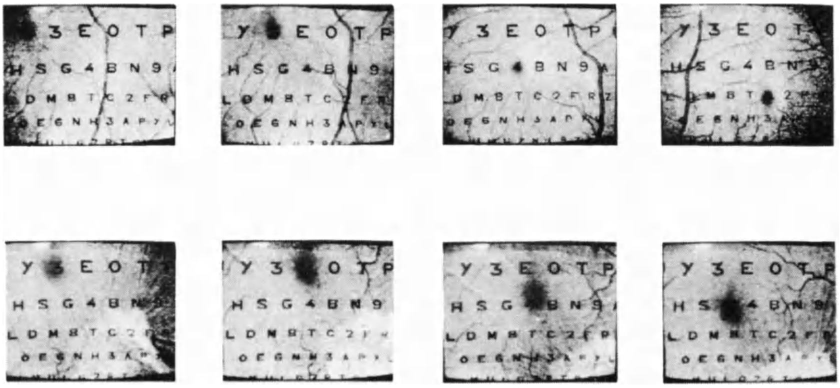
RETINOGRAPHY
λ=514nm.



FLUORESCEIN ANGIOGRAPHY
λ=488nm.

LOCAL STIMULATIONS OF RETINA

ANY GRAPHICAL TEST (ACUITY TARGETS , IMAGES DISPLAYED ON A MICRO-COMPUTER MONITOR ....)
+ VIDEO-CAMERA + ACOUSTO-OPTIC MODULATOR
↳ INTENSITY MODULATION OF ILLUMINATION LASER BEAM
↳ WRITING AND GENERATING IMAGES ON THE RETINA



IT IS POSSIBLE TO ....

- VISUALIZE THE STRATEGY OF THE SUCCESSIVE PATIENT FIXATIONS IN READING...
- STUDY ACCURATELY VISUAL EVOKED POTENTIALS ↳ NEUROPHYSIOLOGY
- LOCATE SCOTOMA

THE RELIABILITY OF THE NAC-V - A PRELIMINARY TEST

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The Nac-V system uses the corneal reflection of both eyes with a left (○) and right (□) eye marker calibrated to indicate the point of regard within a 60° x 45° visual field. The registration part consists of a headmounted goggle and a transportable recording-system. The system also contains a data output unit for automatic data processing. This part of the system is not, however, used in this experiment. All analyses are done manually frame by frame.

The experiment:
Subjects: 6 adults 25-44 years of age, 7 teenagers 14-15 yrs., 7 children 9-11 yrs., and 3 children 7 yrs. of age. All with normal sight except one adult using contact lenses and one teenager wearing glasses.

Apparatus: In order to increase the stability, the goggle was provided with two rubber straps passing over the top of the head and one behind the neck. With the youngest children the two semi-transparent mirrors on the goggle were slightly turned to make possible the calibration of both eyes. A video-timer activated by the subject marked the time of each fixation during the test.

Task: Each S sitting in a chair had to fixate each of 16 red lights on a rosette from a distance of 221 cm on each of two consecutive runs. Each run started and ended with a fixation of the central light - the origin. The visual angles of the distances of the lights from the origin are shown in fig. 1.

Instructions: For the calibration S was asked to fixate the origin and keep it steady for the final part of the mechanical calibration. For the electrical calibration of the two eye-markers S was asked to fixate the nearest light to the right and above the origin in order to calibrate the x- and y-coordinates of the eye-markers.

Fig. 1-4: 16.1°: Lightmarked point of fixation 16.1° visual angle from origin or central light
□,○: Right and left eye-mark during fixation of light.
numbers 1-5: see results part 1 to 3.

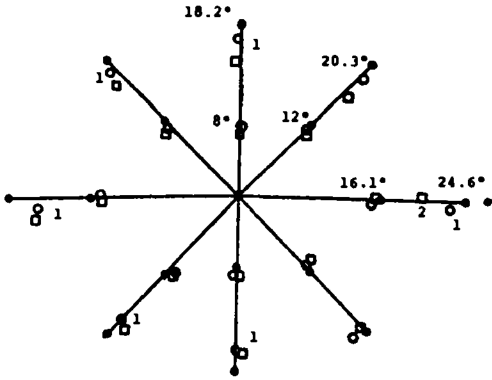

Fig. 1: subj. no. 4, 44 yrs. Eye markings in complete symmetry within the narrower visual field of 16°x8°; virtually no deviation even further to the periphery, but with a shortening in most directions (1&2) and a few cases of ipsi-lateral shortening (2).

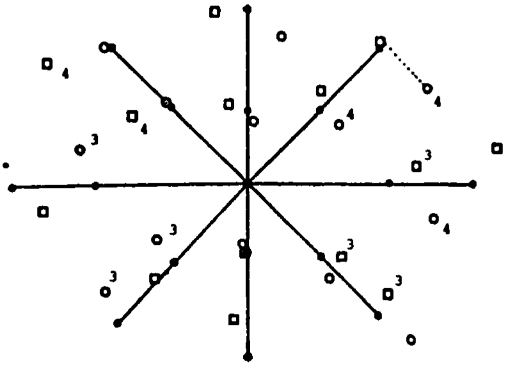

Fig. 2: S. no. 12, 15:2 yrs. There is some asymmetry even in the narrower field; a rather small shortening effect. But a distinct deviation going upwards to the ipsilateral part of the visual field (3) and downward on the contralateral part (4).

RESULTS

1. The electrical calibration to the peripheral lights (see fig. 1-4): The assumed symmetry of movement of the two eye-markers is only partly corroborated in this preliminary test. As to the magnitude of movement during a change of fixation a general increased shortening in the movement of the markers is found toward the periphery (1) (numbers refer to points of fixation in fig. 1-4): When correctly calibrated to 16° to the right of the origin, there is a variable tendency for the eye-mark to fall short of the point 24,6° in the same direction.

2. This shortening of magnitude is not always symmetrical for different directions from the origin. In some cases one finds a more pronounced shortening to the ipsilateral side (2) compared to the marker of the contralateral eye.

3. Besides these shortenings one also finds a variable deviation of the eye-markers toward the periphery. A typical pattern here, but not without exceptions, seems to be an upward deviation to the ipsilateral part of the visual field (3) and a corresponding downward deviation to the contralateral part of the visual field (4) in the horizontal plane.

4. The two phenomena of shortening and deviation are not only a function of each subject; a few repeated tests on the same subject showed a change in the magnitude of both, but the tendencies remained the same.

DISCUSSION

More precise eye-markings can, of course, be obtained by restricting head and body movements, by using adults good at maintaining a steady fixation and with suitable head dimensions, and by taking more time with the calibration procedure. For such purposes another recording device might be more appropriate. The point of this experiment is more to show that in order to obtain optimal recordings with the NAC-V, each recording session should be preceded by a registration of the specific precision of the origin calibration, shortening, and deviation patterns. With suitable data processing it should be possible to neutralize these effects and so increase the precision of the automatic computations and graphs of the fixation-patterns.

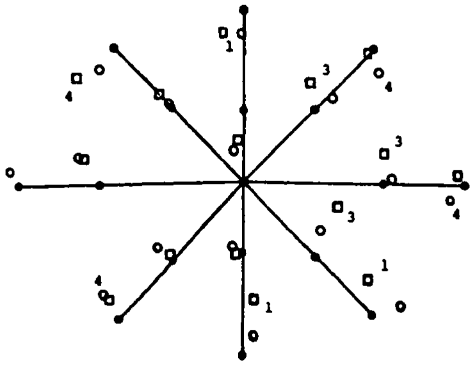

Fig. 3: Subj. no. 15, 10:11 yrs. Eye-marks show a shortening in some directions (1) but without marked ipsi-contralateral differences in magnitude. There are some deviations conforming to the ipsi-contralateral pattern (3&4).

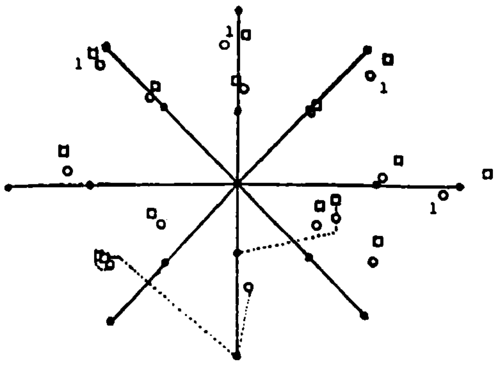

Fig. 4: Subj. no. 21, 7:3 yrs.: Eye-marks are only reasonably precise in the upper part of the visual field. Downward relative to the origin one one finds a very pronounced shortening as well as deviation. Also the upper part is shortened toward the periphery and there are slight deviations.

A MICRO COMPUTER BASED SYSTEM FOR THE ANALYSIS OF SACCADIC EYE MOVEMENTS

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The examination of eye movements was one aspect of a detailed study of reading in school children. Eye movements were recorded onto a Racal FM tape recorder using the sclera reflectance technique during simple sequential tracking tasks and during the silent reading of a passage of prose.

The brief of this project was to design a microcomputer based system to retrieve the recorded eye movements and to display them on a monitor for selection by an operator, to be analysed by the computer. The analysis was to comprise identification and quantification of fixations and saccadic movements. The results of analysis were to be stored in a form suitable for subsequent transmission to a mainframe computer for further statistical analysis.

The system was developed on a popular 8-bit microcomputer, the Apple //e. The advantage of this machine being its portability, cost and availability. The software used was Apple Pascal Version 1.2 and 6502 assembly language for the time critical sections of the system (the Sampling/Display and Racal remote-control routines).

Data Acquisition and Display:

The sampling of the recorded eye movements takes place in frames of approximately 9-second duration, the Racal recorder being automatically started and stopped by program control. During sampling, data is saved into a buffer in Random Access Memory (RAM) and plotted onto the screen. Data is sampled every millisecond, but plotting only occurs every 40 msecs, enabling the display of the entire 9 second recording on the screen.

Delimiting of Trace:

A need was recognised for human intervention to distinguish the meaningful portions of any data tape and to associate these with separate tasks and subjects. Thus a method for delimiting or selecting areas of the eye movement traces was required. The method devised is graphically-based and involves an operator moving a bar across the screen, controlled by the cursor movement keys on the computer. When the operator is satisfied that the bar is at the beginning of a trace this point is marked by pressing the **space** or **return** key. The operator then marks the end point in a similar manner. When an area has been selected in this way analysis can take place.

We chose as the criteria for *start* and *end* of a trace the return sweeps preceding and following a tracking task or reading of a line of text. To facilitate the marking of these the capability to "zoom in" to the data was also included, giving the operator a view of the data at the rate at which it was sampled into the computer, 1 sample/msec. In this mode the operator can page forward or backward from the current position.

Analysis:

The fundamental job of the analysis routine is to recognise the beginning and end of fixations and saccadic movements. A number of algorithms of different complexity have been investigated.
The lowest level procedures detect changes from fixation to movement. The simplest method ,and that which was evaluated first, can be expressed in pseudo-code as follows:

```
Advance the Pointer
If the absolute value of
        (signal at Pointer) - (signal at (Pointer -Lookback))
        is greater than Noise Threshold
then movement has been detected
```

{where Pointer is a pointer to the data buffer, and Lookback is an interval over which comparison is made}

This algorithm tended to break down in places where there were very transient changes in signal, and fixations and movements were detected where there were none.
A higher level filter was introduced which specified threshold levels for minimum fixation time, mininum movement time and distance. Movements or fixations not satisfying these criteria were rejected. The success of this method has been judged by comparing results of analysis against the manual analysis of traces made by Dr S. Newman. In a test there was an 80% correspondence between numbers of fixations identified.

At present we are investigating an algorithm which takes more contextual information into account . The algorithm works by advancing a window (of variable width) with a pointer at its centre and comparing the means of the signal values in front of the pointer with those behind, against a noise threshold. The advantage of this method is that it smooths out the data and is much less sensitive to locally noisy areas of trace. The disadvantage is the considerably longer time for computation.

For each analysis the measures derived are :-

- durations of fixation (mean and s.d.)
- magnitude of each eye movement (mean and s.d.)
- number of eye movements and fixations
- number and magnitude of regressive and progressive eye movements

These results, along with measures from the other tasks, are then saved to disk to form a subject record.

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