Myint Swe Khine *Editor*

Visual-spatial Ability in STEM Education

Transforming Research into Practice

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Part I
Introduction

Chapter 1
Spatial Cognition: Key to STEM Success

Myint Swe Khine

1.1 Introduction

The capacity to perceive the visual images accurately, construct mental representations and imaginary of visual information, understand and manipulate the spatial relations among objects have been considered as spatial ability, a powerful indicator of personal quality and individual differences. Past and present studies reveal the significant correlations between spatial ability and success in science, technology, engineering and mathematics courses and to some extent, gender. Some researchers suggest that spatial ability is malleable and can be improved with interventions, enrichment and training activities. There is currently a renewed interest in visual and spatial reasoning skills to identify the talented students and encourage them to pursue the science, technology, engineering and mathematics (STEM) related careers and function well in techno-centric world.

This book attempts to address in defining spatial abilities, ways to measure them, impact and how it can affect learning subjects in scientific domains. Each chapter in this book provides unique contribution to the body of the literature and enhance the understanding of spatial ability and its influence on learning. The aim of this book is deliberately broad to cover wide ranging topics and perspectives from cognitive psychology, educational psychology, science, technology, engineering and mathematics disciplines and human development. The topics covered in this book are defining spatial ability and its factors, measurement of spatial ability and psychometric analyses, educational strategies to improve spatial skills and implication to science and technology education. It is hoped that information contained in this book will provide knowledge growth and current thinking about visual-spatial abil-

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ity, spatial reasoning, spatial cognition and spatial intelligence. The book is organized in two parts. While Part 1 introduces the measurements and development of spatial ability, Part 2 covers research and practices in spatial ability in different educational settings.

1.2 Measurements and Development of Spatial Ability

Part 1 begins with the chapter by Johnson, Barron, Rose and Carretta from the US Air Force. Johnson and co-investigators presented the validity of spatial ability tests for selection into Science, Technology, Engineering and Mathematics (STEM) career fields with the examples from the military aviation sector. In their chapter (Chap. 2) the authors reviewed the research literature on the validity of spatial ability tests for predicting performance in STEM fields and examined the validity of spatial ability tests compared to verbal and quantitative measures for predicting training outcomes of aircrew and pilots. The chapter presents three studies that show that spatial ability tests add substantive incremental validity to measures of numerical and verbal ability for predicting pilot training outcomes. The authors recommended that future studies should explore to discover which combination of spatial cognition tests would maximize incremental predictive validity over the traditional tests.

In Chap. 3, Nagy-Kondor from the University of Debrecen suggested that spatial visualization skills are important to be successful in several academic disciplines including technical education, mathematics and engineering subjects. Past studies consistently pointed out that there is a correlation between various measures of spatial skills and performance in the STEM subjects. The author described various tests that measures spatial abilities that include Mental Cutting Test, Purdue Spatial Visualization Test, Mental Rotation Test, and Heinrich Spatial Visualization Test. Among these tests visualization of rotation is widely used to measure the spatial ability. The author presents other tests that utilize interactive animation and virtual solids in training spatial skills with the use of Dynamic Geometry Systems.

A test development study to measure spatial visualization is presented by NazanYukselin Chap. 4. The author describes the development of new test to measure spatial visualization ability with the use of contextual items specifically related to mathematics. The test consists of 29 items that cover six different types of questions. The test is designed to find out whether the student can (i) determine the three-dimesional form of geometric shapes after they are rotated around an axis of two-dimensional geometric shapes, (ii) determine the three-dimesional shapes resulting from which two-dimensional geometric shapes after rotating around any axis, (iii) identify the close state of a three-dimensional object from a given open state, and (iv) identify the open state of three-dimensional object from a given close state. The test was administered to 236 students who are studying in mathematics and mathematics education programs and various statistical analyses were conducted. The chapter reports the findings and the author concluded that the test achieved high level of reliability and validity.

In Chap. 5, Lu Wang from Ball State University, USA presented the various spatial skills, gender differences and trainability and transferability of spatial skills. The author attempted to clarify the conceptual distinctions among terms that have been used interchangeably in the literature. These include spatial perception, mental rotation, spatial visualization, mental imagery and visuospatial working memory (VSWM). The focus of the chapter is the review of the findings on the association between numerical magnitude and space, and predictive relationship between spatial skills and mathematics achievement. The literature suggests that spatial abilities are malleable through interventions. The author cautions that it is important to investigate the effect of longer duration spatial intervention programs and its long-term impact.

1.3 Research and Practices in Spatial Ability

Part 2 of the book begins with the chapter by Jonathan Wai from Duke University, USA and Harrison Kell from Educational Testing Service, USA. In their chapter (Chap. 6) the authors describe the importance of identifying and developing spatial talent among students. They observed that standardized tests commonly used in schools today did not include spatial ability measures and as a result many spatially talented students are not being identified. The chapter reviews over 50 years of data that shows that spatial ability, in addition to mathematics and verbal ability has predictive power in STEM domains. In the area of spatial ability training the authors caution to make the distinction between training the *trait* of spatial ability and providing spatially enriched *education* to develop spatial mode of thinking.

In Chap. 7, Maria Fastame noted that the development of visuo-spatial abilities plays a crucial role in many scholastic achievement including problem solving skills. In this chapter the author presents the development of visuo-spatial working memory in early life span and the impact of such abilities at school and described the effect of Non-Verbal Syndrome. The author cited the literature that suggests that children with spatial abilities deficits can be benefitted by the training aimed at enriching such abilities. The author then described the specific training and intervention strategy that could help in visuo-spatial cognition. The training includes enrichment of different aspects of non-verbal abilities, visuo-motor coordination and non-verbal long-term memory. The author suggests the importance of active exploration of environment to improve the spatial cognition among children.

On the topic of improvement of spatial ability among students, Cheng from Michigan State University, USA examined whether the existing tests measure what they are supposed to measure. In Chap. 8 she discusses the psychometric properties of some of the instruments and how spatial ability is assessed and the way it relates to spatial training. The chapter begins by defining spatial ability and described some types of spatial measures such as water level task, mental rotation, visual spatial working memory task and map reading task. The chapter also examines whether spatial ability can be improved by training and its effects on STEM achievement. In

Chap. 9, Melih Turgut from Eskisehir Osmangazi University in Turkey describes about the process of visualization and spatial thinking. This chapter is devoted to the spatial thinking process in ICTs from a semiotic perspective. The chapter reviews the ways of spatial thinking in geometry and mathematics education using 3D modeling software and presented two case studies on the use of 3D modeling software (SketchUp®) to evaluate the spatial – semiotic framework.

Reilly, Neumanna and Andrews (Chap. 10) noted that while men and women do not differ in levels of general intelligence, gender differences exist for more specific cognitive abilities. They observed that males score higher in tests of visual spatial ability and gender gaps in spatial ability are the largest of all gender differences in cognitive abilities. Studies show that spatial ability is linked to mathematics and science achievement and influence on success of STEM related subjects. The authors noted that instruction and practice can yield improvements in performance on spatial tasks, reducing the magnitude of gender differences. They suggest that early education of spatial intelligence is necessary to benefit the later development of mathematical and scientific skills across all ability levels. Parents and caregivers can also encourage children by using spatial language, providing children with enrichment activities that offer spatial learning experiences. The chapter presents theoretical perspectives on origins of gender differences and interventions for spatial ability training. The authors provide future directions and research in this area.

Martín-Gutiérrez and González from the University of La Laguna in Spain reiterated the fact that spatial abilities can predict both entrance into STEM occupations and performance on STEM-related tasks and how spatial ability can contribute to creativity and academic outcomes in STEM domain in Chap. 11. The authors describe several training programs that can improve spatial ability and develop mathematic models to predict which type of training can contribute improvement in spatial skills. The strategies used to improve the spatial ability is a training that involves videogames, augmented reality, sketching and descriptive geometry. After going through the training, posttest measures on spatial ability are conducted and data was analyzed. The authors found that the linear model is the most suitable choice for predicting the improvement of spatial abilities regardless of the type of training performed. They also found that the training with videogames most improves the spatial ability and a duration of 10 h of training could help to significantly improve the spatial ability among students.

In Chap. 12 Crollen and Noel from Belgium examine the spatial ability of the individuals from the point of view of interaction between number and space and describe about the Spatial – Numerical Association of Response Code (SNARC) effect. The authors show that spatial and numerical representations are intrinsically linked and visuo-spatial weaknesses can result in numerical deficits. The authors also note the effect of visuo-spatial working memory could be the key factor in numerical processing and suggest that providing training might have positive impact on specific mathematical difficulties.

1.4 Conclusion

Theoretical knowledge and empirical evidence of spatial cognition has progressed remarkably in the past decades. Much of the literature on spatial ability and success in science and engineering related fields demonstrated a clear link between spatial cognition and STEM success (Kell and Lubinski 2013; Hegarty 2014; Taylor and Hutton 2013). For example Uttal and Cohen (2012) explored the relation between spatial thinking and performance and attainment in STEM domain and suggested that spatial skills strongly predict the selection of students to study STEM subjects. The authors noted that psychometrically-assessed spatial abilities predict performance in early STEM learning. Similarly, Hinze et al. (2013) found that spatial visualization abilities are positively related to performance on science, technology, engineering, and math tasks. In their study chemistry students observed and explained sets of simultaneously presented displays depicting chemical phenomena at macroscopic and particulate levels. Eye movement analyses revealed that greater spatial ability was associated with greater focus on the prediction relevant macroscopic level.

In recent years researchers have been exploring the possible solution for improving the spatial ability and STEM achievement (Stieff and Uttal 2015) and found the malleability of spatial skills where students can be trained to improve these skills (Uttal et al. 2013). The study conducted by Sorby et al. (2013) involves intervention of spatial training course for freshman engineering students to improve the mental rotation skills. The authors reported that the intervention group scored at higher level of spatial ability and calculus performance after the training. In order to investigate the role of spatial training in improving mathematics ability, Cheng and Mix (2014) provided a mental rotation training to elementary students. It was reported that those in the spatial training group improved significantly on calculation problems. Findings from these studies encourage the teachers in attempting to enhance the spatial ability among students and improve the performance in STEM related subjects. The contributors to this volume have considered challenges and potentials of measuring, training and developing spatial abilities and presented their thoughts, ideas and findings. It is hoped that this collective and collaborative work will continue and lead to more ground breaking discoveries in this area.

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Part II

Measurement and Development of Spatial Ability

Chapter 2
Validity of Spatial Ability Tests for Selection into STEM (Science, Technology, Engineering, and Math) Career Fields: The Example of Military Aviation

James F. Johnson, Laura G. Barron, Mark R. Rose, and Thomas R. Carretta

2.1 Introduction

Quantitative and verbal aptitude tests enjoy extensive use in the context of student admissions and organizational pre-employment screening/selection systems. Traditional measures of general cognitive ability found in many standardized tests are strong, positive predictors of both academic (Frey and Detterman 2004; Jensen 1998; Kuncel et al. 2001) and occupational (Hunter 1986; Jensen 1998; Schmidt and Hunter 2004) success. However, for civilian and military STEM (science, technology, engineering, and mathematics) fields, research additionally suggests spatial ability is a critical predictor of field and career success (National Research Council [NRC] 2015; Lubinski 2010; Uttal and Cohen 2012; Wai et al. 2009). Wai and colleagues (2009) demonstrate spatial abilities play a critical role in predicting adolescent achievement in STEM careers above quantitative and verbal ability, and characterize the failure to improve talent identification via spatial ability assessment nothing less than “contemporary neglect” (p. 817). Similarly, Lubinski (2010) asserts identification of spatial ability is a proverbial “sleeping giant” for improving identification and development of talent in STEM fields.

Most research linking spatial ability with STEM education and career success involves assessment of spatial visualization. Spatial visualization is the process of apprehending, encoding, and mentally manipulating spatial forms within and between one, two, or three-dimensional space (Carroll 1993; Uttal and Cohen 2012). Other forms of spatial ability include visual memory, closure and perceptual speed, and kinesthetic coordination (Carroll 1993; NRC 2015). Spatial ability has

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consistently demonstrated moderate-to-strong correlational relationships with and predictive validity of performance in STEM fields including human physiology (Rochford 1985), radiology and dentistry (Hegarty et al. 2007), geology (Hambrick et al. 2011), chemistry (Stieff 2004, 2007), and mathematics (Koedinger and Anderson 1990). In a broad review of spatial abilities and STEM field success, Uttal and Cohen (2012) conclude spatial cognition is most predictive of STEM performance and success when participants lack domain-specific knowledge; heightened spatial ability may serve to facilitate integration of STEM-related concepts into undeveloped mental models. However, as field-specific STEM knowledge increases via educational attainment and applicable mental models are developed and refined, the relative impact of spatial ability decreases (Ackerman 1988; Hambrick et al. 2011; Hambrick and Meinz 2011). Thus, for those new to STEM fields, initial spatial ability may set the trajectory for long-term success.

Not only does spatial ability predict STEM field career success, it adds incremental predictive validity beyond predictors of quantitative and verbal aptitude on standardized tests like the Scholastic Aptitude Test (SAT) (Shea et al. 2001; Webb et al. 2007) and the Graduate Record Exam (GRE) (Wai et al. 2009). Wai and colleagues (2009) summarize and extend five decades of spatial abilities research examining a sample of 400,000 high school students (grades 9 through 12) tracked via Project TALENT in the 1960s and 1970s (Wise et al. 1979) along with contemporary GRE data and the Study of Mathematically Precocious Youth (Lubinski and Benbow 2000). The authors demonstrate mathematical and spatial ability are the two greatest predictors of STEM career success and degree attainment, and that spatial ability predicts success in STEM fields beyond just mathematical aptitude.

Ambivalence to adopt spatial abilities testing in talent identification and selection can be partially attributed to reported gender differences on spatial ability measures (see Linn and Peterson 1985) and persistent under-representation of women in STEM fields (Ceci et al. 2009; Halpern 2012; Wai et al., 2009). Further complicating gender differences are the impact of cultural influence and gender stereotypes. For example, males consistently provide higher *self-estimates* of general, mathematical, and spatial ability over their female peers (Syzmanowicz and Furnham 2011). However, gender differences in spatial ability are also a function of the spatial ability being assessed, the test used, and gender composition of testing samples (Barron and Rose 2013; Linn and Peterson 1985; Miller and Halpern 2013). Ultimately organizations must weigh potential advantages and disadvantages of assessing spatial ability when selecting candidates for highly-specialized organizational roles.

One highly-specialized, applied STEM field is military aviation. In the United States Air Force (USAF), combat systems officers (CSO) serve as mission commanders of multi-person aircraft, coordinating electronic warfare and intelligence, weapons systems, and navigation/communications (Olea and Ree 1994). Air battle managers (ABM) provide “big picture” command and control support for air missions, ranging from risk management to location, identification, and pursuit of enemy targets (Carretta 2008; Miller 1997). In the cockpit pilots simultaneously operate complex machinery while maintaining “continuous perception of self and the aircraft in relation to the dynamic environment of flight, threats, and mission" and the ability to forecast and execute tasks (Carretta et al. 1996, p. 22). Hunter and Burke (1994) meta-analyzed decades of aviation research noting assessment of spatial ability has substantial cost benefits for military pilot selection. In USAF pilot trainees, spatial ability positively predicts training grades (i.e., academic, daily flight, check flight, and class rank) as well as pilot training graduation/attrition. A meta-analysis across 11 countries (Martinussen 1996), and recent international studies (de Kock and Schlecter 2009; Maroco and Bartolo-Ribeiro 2013) further support the validity and generalizability of spatial abilities for predicting pilot training success. Extending past training, seasoned USAF pilots demonstrate better metric spatial relation as well as mental rotation in relation to their non-pilot counterparts (Dror et al. 1993; King et al. 2013). Spatial ability also plays a role in ameliorating spatial *disorientation*, a critical skill in military aviation during high-pressure combat missions and immediate threat situations (Webb et al. 2012).

The U.S. military is the largest employer of young adults ages 18–29, and military aviation frequently involves training applicants with little or no prior aviation experience (Dickinson 2012; Hunter and Burke 1994). Recalling the critical role initial spatial ability has in the trajectory of success for those lacking domain-specific expertise (Hambrick et al. 2011; Hambrick and Meinz 2011), military aviation has a vested interest to accurately identify, select, and classify spatial talent. In this chapter we examine the role spatial ability plays in predicting primary flight training outcomes for USAF pilot and aircrew trainees. First, we examine similarities between spatial ability and perceptual speed tests, determining them to be facets of spatial cognition. We additionally examine how spatial cognition tests (including both two and three-dimensional spatial ability and perceptual speed measures) differ from quantitative and verbal ability. Second, we use a meta-analytic approach to examine the relative predictive validity of spatial cognition tests relative to quantitative, verbal, and technical knowledge tests. Finally, we examine incremental predictive validity of spatial cognition tests above traditional quantitative and verbal aptitude for predicting "hands on" flying and academic pilot training success.

2.2 Method

Before entering aircrew training, all USAF officer candidates are screened on the Air Force Officer Qualifying Test [AFOQT] (Caretta and Ree 1996; Drasgow et al. 2010; Skinner and Ree 1987), a battery of ability tests including both traditional academic aptitude (verbal, quantitative) measures like those included on the SAT/ACT or in other college admissions testing, as well as several non-academic aptitude measures assessing spatial ability and technical knowledge. AFOQT scores are used to award US Air Force Reserve Officer Training Corps (AFROTC) scholarships and to qualify applicants for officer commissioning through ROTC, Officer Training School (OTS), and the Airman Education and Commissioning Program (AECP). It also qualifies applicants for aircrew training specialties such as combat system officers (CSO; formerly navigators), air battle managers (ABM), and remotely-piloted aircraft (RPA) pilots provided they clear other educational, fitness, medical, moral, and physical requirements (Carretta 2008; Carretta and Ree 1995; Olea and Ree 1994).

2.3 Study 1 Method: AFOQT Factor Analysis

We examine five academic subtests most similar to those used in traditional college admissions testing as well as seven distinct AFOQT aptitude subtests with a spatial component. While the AFOQT itself has evolved over time, we focus on form Q used from 1994 to 2005 which included a larger number of spatial ability and perceptual speed tests in operational classification compared to AFOQT forms S and T (see Figs. 2.1 and 2.2) (Air Force Personnel Testing 2014; Carretta 2008; DSYX 2015; Weissmuller et al. 2004). Academic tests include Reading Comprehension,

Academic Test	*Q*	*S*	*T*	*Test Description*
Reading Comprehension	x		x	18-minute, 25-item subtest in which applicants are assessed on ability to read and understand paragraphs.
Verbal Analogies	x	x	x	8-minute, 25-item subtest in which applicants are asked to reason and see relationships among word pairs.
Word Knowledge	x	x	x	5-minute, 25-item subtest in which applicants are tested on their knowledge of words and their meaning.
Arithmetic Reasoning	x	x	x	29-minute, 25-item subtest in which applicants are asked to use basic arithmetic to solve math problems embedded in short paragraphs
Math Knowledge	x	x	x	22-minute, 25-item subtest in which applicants are tested on their knowledge of mathematical terms and principles

Fig. 2.1 Academic subtests administered as part of the AFOQT from Form Q through current Form T. An "x" denotes test was used in officer selection while shaded squares indicate test administration but no use in officer selection

Spatial Test	*Q*	*S*	*T*	*Test Description*
Block Counting	x	x	x	3-minute, 20-item subtest in which applicants view a three-dimensional pile of blocks and, given a certain numbered block, determine how many other blocks it touches.
Electrical Maze	x			10-minute, 20-item subtest in which applicants choose the correct path in a maze. The correct path must pass through a waypoint (circle), and make turns only where allowed.
Hidden Figures	x	▨		8-minute, 15-item subtest in which applicants must determine which simple figure is hidden within a complex drawing.
Mechanical Comprehension	x			22-minute, 20-item subtest in which participants are measured on their knowledge of mechanical items, principles, and understanding of mechanical devices.
Rotated Blocks	x	▨		13-minute, 15-item subtest in which participants are asked to visualize and manipulate three-dimensional objects in space.
Scale Reading	x			15-minute, 40-item subtest in which applicants are are tested on their ability to read a variety of scales, dials, and meters.
Table Reading	x	x	x	7-minute, 40-item subtest in which applicants are tested in their ability to read a table quickly and accurately using X and Y value coordinates.

Fig. 2.2 Spatial subtests administered as part of the AFOQT from Form Q through current Form T. An "x" denotes test was used in officer selection while shaded squares indicate test administration but no use in officer selection

Verbal Analogies, Word Knowledge, Arithmetic Reasoning, and Math Knowledge. Spatial-based tests include Block Counting, Electrical Maze, Hidden Figures, Mechanical Comprehension, Rotated Blocks, Scale Reading, and Table Reading. For sample spatial test questions see Appendix A. Although several published analyses have documented the evolving factor structure of the AFOQT (c.f. Carretta and Ree 1996; Drasgow et al. 2010; Glomb and Earles 1997; Skinner and Ree 1987), for ease of interpretation, the two AFOQT subtests assessing prior aviation knowledge and exposure (Aviation Information and Instrument Comprehension) are excluded from our analysis to more readily focus on aptitude and not prior knowledge. Additionally, Form Q quantitative subtest Data Interpretation is excluded to better replicate the quantitative composite used in operational AFOQT form T (i.e., Arithmetic Reasoning and Math Knowledge only) (DSYX 2015).

Between February 1994 and September 2006, 34,184 AFROTC officer candidates completed the AFOQT form Q, of which 30,025 ROTC candidates had AFOQT subtest-level data available in the Defense Manpower Data Center (DMDC) database. Candidates were predominately male (74.41 %) and were on average 20.02 years old. Demographically, 76.66 % of candidates indicated as White/Caucasian, 8.79 % African-American, 5.46 % Asian-American, 0.82 % Native-American, 0.30 % Pacific-Islander; 8.52 % declined to provide demographic data. For study one we completed a principal components analysis of the 13 non-aviation-specific subtests using an orthogonal varimax rotation, examined associated scree plots, and retained factors with Eigenvalues >1.

2.4 Study 1 Results: AFOQT Factor Analysis

Initial correlations between subtests were calculated with results indicating a significant degree of inter-correlation between subtests and evidence of subtest factorability [Table 2.1: $rs = .13–.69$, $ps < .0001$]. Results revealed a two-factor structure and adequate fit for the data [Kaiser's sampling adequacy = .90, $\text{RMSR}_{\text{diagonal}} = .07$, $\text{RMSR}_{\text{off-diagonal partials}} = .17$, $\text{commonality estimates}_{\text{final}} > .427$]. A spatial cognition factor [factor loadings = .662–.740] emerged consisting of Block Counting, Scale Reading, Electrical Maze, Rotated Blocks, Table Reading, and Hidden Figures. This spatial factor had an eigenvalue of 5.35 and explained 44.58 % of variance of the factor structure. A second, academic aptitude factor [factor loadings = .831–.877] emerged consisting of verbal aptitude measures Word Knowledge, Reading Comprehension, and Verbal Analogies, with an eigenvalue of 1.53 and explained an additional 12.76 % of the factor structure. Two quantitative aptitude measures (Arithmetic Reasoning, Math Knowledge) and one spatial measure (Mechanical Comprehension) did not readily load on either factor [cross-factor loadings = .502–.575] (Table 2.2). Results indicate where cross-loading existed it was for subtests requiring both a certain academic reading level (i.e., to extract information from word problems or to use certain terminology) as well as specific level of spatial ability (i.e., interpretation of visuospatial diagrams and figures).

Table 2.1 Correlation matrix of AFOQT form Q subtests factor analysis

	AFOQT subtests	Mean	SD	1	2	3	4	5	6	7	8	9	10	11	12
1	Reading Comprehension	15.59	4.80	1											
2	Verbal Analogies	16.23	4.03	.66	1										
3	Word Knowledge	14.20	5.03	.69	.67	1									
4	Arithmetic Reasoning	14.75	5.23	.51	.50	.42	1								
5	Math Knowledge	17.30	5.10	.46	.45	.37	.67	1							
6	Mechanical Comprehension	8.81	4.12	.44	.45	.44	.51	.42	1						
7	Electrical Maze	8.44	3.47	.25	.25	.18	.37	.32	.43	1					
8	Block Counting	12.80	3.79	.30	.30	.21	.43	.36	.37	.42	1				
9	Rotated Blocks	8.67	3.16	.28	.33	.27	.43	.38	.54	.40	.45	1			
10	Hidden Figures	9.59	3.22	.27	.32	.23	.38	.36	.41	.38	.39	.48	1		
11	Scale Reading	25.46	6.88	.38	.36	.26	.61	.49	.42	.42	.52	.43	.39	1	
12	Table Reading	27.01	6.58	.25	.21	.13	.35	.33	.23	.31	.47	.27	.29	.48	1

Note: N = 30,025; All correlations $p < .0001$

Table 2.2 Factor loading results of AFOQT form Q subtests

	Factor 1	Factor 2
AFOQT subtests	(Spatial cognition)	(Academic aptitude)
Reading Comprehension	.193	**.838**
Verbal Analogies	.203	**.831**
Word Knowledge	.051	**.877**
Arithmetic Reasoning	**.575**	**.545**
Math Knowledge	**.508**	**.507**
Mechanical Comprehension	**.513**	**.502**
Electrical Maze	**.667**	.115
Block Counting	**.740**	.134
Rotated Blocks	**.661**	.242
Hidden Figures	**.622**	.201
Scale Reading	**.728**	.270
Table Reading	**.653**	.044

Note: N = 30,025; Factor 1 explains 44.58 % of factor variance; Factor 2 explains 12.76 % factor variance

2.5 Study 1 Discussion: AFOQT Factor Analysis

Results of the subtest-level exploratory factor analysis demonstrate academic and spatial aptitude tests form distinct factors, such that individuals who perform most highly on tests of traditional academic measures are different from those who perform most highly on spatial aptitude measures. Results also demonstrate while distinct spatial aptitude tests may differ in important respects (e.g., two-dimensional vs. three-dimensional rotation, level of speededness) (c.f. Carroll 1993; Fleishman et al. 1999; Hegarty et al. 2006), nonverbal spatial test scores for both spatial ability and perceptual speed converge permitting us to speak about overall (i.e., general) spatial cognition distinct from academic aptitude. This diverges somewhat with earlier work by Carretta and Ree (1996) who examined AFOQT form Q factor structure with spatial ability and perceptual speed as both separate (Model 5) and combined factors (Model 6). The authors assert Model 5 [$\chi^2(83) = 1250$; $RMSEA = .071$; $CFI = .957$; $AASR = .027$] as having a significantly better fit than Model 6 [$\chi^2(84) = 1313$; $RMSEA = .072$; $CFI = .954$; $AASR = .029$], but did not examine fit in terms of parsimony/complexity, a necessity in highly-saturated, complex models (Akaike 1974; Mulaik et al. 1989).

Note findings of our factor analysis are also consistent with spatial abilities literature that frequently includes perceptual speed as a facet of overall spatial cognition (NRC 2015). Carroll (1993) as well as Fleishman and colleagues (e.g., Fleishman et al. 1999; Fleishman and Quaintance 1984) propose perceptual speed as part of spatial cognition involving the ability to quickly compare and match visual objects/stimuli. The National Research Council (2015) notes an emerging consensus that spatial abilities might best be conceptualized by "scale of task" as opposed to "type of task", creating two distinct yet related spatial families: (1) "Small scale" tasks involving mental rotation of objects and (2) "large scale" tasks involving navigation and way-finding (Hegarty et al. 2006). In light of current study factor analysis results and literature denoting perceptual speed as a facet of overall spatial cognition (Carroll 1993; Fleishman et al. 1999; Fleishman and Quaintance 1984), we examine the incremental validity of AFOQT form Q spatial ability *and* perceptual speed tests on academic and hands-on pilot training outcomes.

2.6 Study 2 Method: Meta-analysis of AFOQT Predictive Validity

The use of meta-analytic techniques provides the ability to assess statistical commonality across time and multiple study formats. Study two examines the relative predictive impact of traditional (verbal, quantitative) and non-traditional (spatial, processing speed, specialized knowledge) cognitive abilities on USAF pilot (Carretta and Ree 1995), navigator (Olea and Ree 1994; Valentine 1977), and air battle manager (Carretta 2008) training performance. Total sample size across four studies consisted of 10,161 Air Force officer candidates spanning multiple iterations of the AFOQT.

2.7 Study 2 Results: Meta-analysis of AFOQT Predictive Validity

Meta-analysis of the relative predictive validity of AFOQT subtests was based on data from four studies. The test battery used by Valentine (1997) included AFOQT Form N and several experimental tests. Several of these experimental tests were subsequently administrated and included in later AFOQT validation studies and AFOQT test form versions (O and P) (Carretta and Ree 1995; Olea and Ree 1994). A final article included in the meta-analysis used participants who primarily completed the AFOQT form Q (Carretta 2008). Spatial aptitude content varied across forms of the AFOQT, with five spatial abilities subtests (Blocking Counting, Electrical Maze, Hidden Figures, Mechanical Comprehension, and Rotated Blocks) and two perceptual speed subtests (Table Reading and Scale Reading) being assessed through AFOQT form Q. With development of AFOQT form S, test structure, length, and content were assessed to reduce administration time. Subtests were removed based on two criteria: (1) that removal would minimize impact on total variance explained compared to the 16-subtest AFOQT and (2) the subtest had low or multi-factor loadings (Thompson et al. 2010). Form S retained spatial abilities test Block Counting and perceptual speed test Table Reading for officer candidate selection; spatial tests Hidden Figures and Rotated Blocks were included in Form S but were not part of any operational composite (Drasgow et al. 2010; Weissmuller et al. 2004). As of Form T, only Block Counting and Table Reading are still included in the AFOQT (DSYX 2015).

The meta-analysis examined the predictive validity of several cognitive measures for USAF pilot (Carretta and Ree 1995), navigator (Olea and Ree 1994; Valentine 1977), and air battle manager (Carretta 2008) training performance. Validities of the AFOQT tests were corrected for range restriction (Lawley 1943) and dichotomization (Cohen 1983), and the corrected validities were averaged for verbal, quantitative, spatial, specialized knowledge, and perceptual speed predictor scores. Training performance criteria include graduation/elimination, academic and flight grades, and composite measures of performance. Mean validities for the cognitive constructs varied across occupation and training criteria; quantitative aptitude had the highest mean weighted validity for academic grades: verbal [$\rho = .282$], quantitative [$\rho = .334$], aircrew knowledge [$\rho = .244$], spatial [$\rho = .227$], and perceptual speed [$\rho = .286$]. Perceptual speed and aircrew knowledge had the highest mean weighted validities for hands-on flying criteria [i.e., daily and check flight grades]: verbal [$\rho = .094$], quantitative [$\rho = .182$], aircrew knowledge [$\rho = .209$], spatial [$\rho = .153$], and perceptual speed [$\rho = .218$]. The weighted mean validities across all occupations and criteria from highest to lowest were: perceptual speed [$M_{rho} = .244$], quantitative [$M_{rho} = .225$], aircrew knowledge [$M_{rho} = .219$], spatial [$M_{rho} = .177$], and verbal [$M_{rho} = .145$]. Results are summarized in Table 2.3.

Table 2.3 Summary results of AFOQT predictive validity meta-analyses

				Construct				
Study	Group	Criterion	N	Verbal	Quant.	Spatial	Aviation	PS
Carretta (2008)	ABM	Academic average	680	.3675	.3530	.2097	.3070	.2500
Carretta and Ree (1995)	Pilot	T-6 DFA	7563	.1300	.1989	.1795	.2962	.2461
		T-6 CFA	7563	.1372	.2615	.2230	.3006	.2922
		T-38 DFA	7563	.0312	.0966	.0777	.1187	.1314
		T-38 CFA	7563	.0686	.1643	.1337	.1608	.2044
		Academic average	7563	.2556	.3092	.2071	.2073	.2636
Olea and Ree (1994)[a]	Nav	UNT P/F	1411	.1833	.3233	.2420	.2050	.3150
		Airmanship	1341	.3433	.3800	.2900	.3500	.3350
		Basic procedures	1176	.3333	.4333	.2940	.3250	.4000
		Day CF	1224	.1333	.2033	.1440	.1050	.2200
		Night CF	1182	.1167	.2067	.1580	.0800	.2100
		Overall composite	957	.1100	.2033	.2040	.2950	.2600
Valentine (1977)	Nav	UNT P/F	507	.4685	.4630	.4920	–	.8105
Weighted mean			46,293/45,786	.1450	.2253	.1779	.2195	.2444

Notes: Construct validities were averaged across tests with similar content for verbal, quantitative, spatial, aircrew, and perceptual speed. Validities for Carretta (2008), Carretta and Ree (1995), and Olea and Ree (1994) were corrected for range restriction Lawley (1943). Validities for Valentine (1977) were corrected for dichotomization of criterion Cohen (1983)

[a] Airmanship included instruction on flight instruments and map reading. Basic Procedures included airspace, earth physics, and flight safety training. Day (Day CF) and Night (Night CF) Celestial Check Flight ratings were work samples of actual flight missions, stellar observation, and solar plotting

2.8 Study 2 Discussion: Meta-analysis of AFOQT Predictive Validity

The previous meta-analysis provides a broad examination of the relative predictive validities of traditional (verbal, quantitative) and non-traditional (spatial, processing speed, specialized knowledge) cognitive abilities for US Air Force officer trainees in a variety of military aviation roles. Meta-analysis of AFOQT and officer outcomes indicate the content areas with the highest weighted mean validities across all criteria were perceptual speed, quantitative, and aviation knowledge. Verbal and quantitative aptitudes demonstrate consistently greater predictive validity for traditional academic performance outcomes than do spatial ability or perceptual speed. Spatial ability, aviation knowledge, and perceptual speed demonstrate their highest validity for indicators of "hands-on" pilot performance including basic procedures, daily flight, and check flight outcomes; Quantitative ability also predicts pilot-related outcomes. This is not surprising considering the established statistical relationship between quantitative aptitude, spatial ability, and STEM field success (Uttal and Cohen 2012; Wai et al. 2009).

Study three further explores the predictive relationships of such measures by demonstrating the incremental predictive validity of spatial cognition when used in combination with verbal and quantitative aptitude tests for predicting "hands-on" and academic pilot training outcomes.

2.9 Study Three Method: Spatial Cognition Incremental Validity

2.9.1 Overview

In light of our factor analysis of AFOQT form Q in study one and predictive meta-analysis across multiple AFOQT forms in study two, we examine the incremental predictive validity of spatial ability and perceptual speed subtests on daily flight and academic performance for USAF pilots. We identified 905 ROTC officer candidates with valid AFOQT form Q subtest scores and undergraduate pilot training outcome data. These pilot trainees completed the AFOQT between November 1998 and August 2005, attended Specialized Undergraduate Pilot Training (SUPT) between 2001 and 2008, and included pilots who trained in both the older USAF T-37 and the newer T-6 training aircraft.

From 2001 to 2008 the USAF phased out the Cessna T-37 Tweet basic flight training aircraft in favor of the more modern Beechcraft T-6 Texans II (Parie 2008). Critical differences exist between aircraft including increased power and maneuverability in the T-6, a pressurized, digital glass cockpit with Head-Up Display (HUD), and several additional multifunction displays lacking in the T-37 (USAF 2003; USAF National Museum 2015). Periods of aircraft training transition impact both flight instructors and trainees (O'Neil and Andrews 2000), and evidence of transitional impact was observed on pilot trainee daily flight performance evaluation scores in our sample. Trainee daily flight scores for T-6 trainees were significantly lower in 2006 [$M=64.72$, $SD=4.61$] and 2007 [$M=65.99$, $SD=5.03$] than in 2008 [$M=66.61$, $SD=5.44$], [$F(2625)=6.77$, $p<.002$], but not for trainees during the same time period still training in the T-37, $F(2300)=2.84$, *n.s.* Therefore we eliminated T-6 trainees in 2006 and 2007 [$N=360$], only including those from 2008 as mean daily flight scores were comparable to 2008 T-37 daily flight scores, $M=66.68$, $SD=3.86$. In total, 640 (71 %) participants completed basic flight training using the T-37 aircraft while 265 (29 %) trained with the newer T-6.

2.9.2 Performance Criteria

While in SUPT trainee performance is evaluated via a number of hands-on flying and academic criteria. The current study examines two criteria, one related to "hands-on" daily flight performance and the other related to aviation academic testing performance. Individual daily flight performance involves assessment of trainee skill and ability to execute basic and advanced flying maneuvers and procedures including emergency landing pattern, missed approach, and speed break maneuvers on all flights except check flights (Barron and Rose 2013; Carretta and Ree 1995). Trainee flight performance is assessed daily by instructor pilots during each sortie or mission using a one to five grading scale (no grade/unable or unsatisfactory/fair/good/excellent), providing a consistent and multi-point metric of daily flight performance (Barron and Rose 2013). Daily performance percentage scores are then computed by dividing number of maneuver points obtained by number of maneuver points possible. Academic performance is assessed via written tests of flying fundamentals including procedures, aerodynamics, navigation, aviation meteorology, mission planning, and mishap prevention. The majority of academic assessment takes place during Phase I of primary pilot training, prior to actual flight training (Carretta and Ree 1995; O'Neil and Andrews 2000).

2.10 Study Three Results: Spatial Cognition Incremental Validity

2.10.1 Daily Flight Performance

Initial correlations between subtests and outcome variables were calculated, indicating a significant degree of inter-correlation between predictor and outcome variables [Table 2.4: $rs = .07–.61$, $ps < .05$]. Using the AFOQT form Q we examined which composition of the five traditional cognitive AFOQT form Q subtests (Reading Comprehension, Verbal Analogies, Word Knowledge, Math Knowledge and Arithmetic Reasoning) were predictive of daily flight performance. All five subtests were entered into a preliminary regression analysis predicting daily flight performance; non-significant subtests Verbal Analogies and Word Knowledge were removed through the process of backwards elimination, $p > .05$. Quantitative predictors Math Knowledge and Arithmetic Reasoning were summed to create a basic quantitative composite score to reflect the composite used in the current AFOQT form T (DSYX 2015). Finally, the quantitative composite and Reading Comprehension subtest variables were entered into a second regression equation predicting daily flight performance. Results indicate both the quantitative composite [$\beta = .17$, $p < .0001$] and Reading Comprehension subtest [$\beta = .10$, $p < .01$] were significant, positive predictors of participant daily flight performance, $F\ (2905) = 25.97$, $p < .0001$, $R^2 = .055$).

Table 2.4 Correlation matrix of AFOQT form Q subtests incremental validity

	Variables	Mean	SD	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Reading Comprehension	17.18	4.11	1													
2	Verbal Analogies	17.52	3.29	.54	1												
3	Word Knowledge	15.42	4.45	.61	.56	1											
4	Arithmetic Reasoning	16.47	4.60	.39	.37	.26	1										
5	Math Knowledge	18.50	4.51	.32	.30	.25	.58	1									
6	Mechanical Knowledge	11.14	3.60	.30	.36	.32	.36	.27	1								
7	Electric Maze	9.78	3.25	.14	.14	.09**	.23	.19	.28	1							
8	Block Counting	14.28	3.36	.16	.18	.10**	.28	.17	.19	.33	1						
9	Rotated Blocks	10.07	2.65	.11**	.18	.14	.28	.26	.38	.26	.31	1					
10	Hidden Figures	10.80	2.94	.16	.22	.15	.26	.21	.24	.26	.28	.34	1				
11	Scale Reading	28.70	5.75	.25	.22	.10	.50	.33	.22	.23	.36	.26	.25	1			
12	Table Reading	29.64	5.84	.15	.13	.07*	.27	.20	.12	.23	.35	.11	.16	.34	1		
13	Daily flight score	49.21	9.43	.17	.12	.10**	.21	.17	.21	.11	.15	.19	.14	.23	.22	1	
14	Pilot academic score	49.12	10.19	.29	.23	.19	.33	.33	.29	.12	.13	.22	.13	.19	.13	.47	1

Note: $N = 905$; $^{*}\ p < .05$, $^{**}\ p < .01$; All other correlations at least significant at $p < .001$

Table 2.5 Spatial incremental validity on daily flight performance

	β	SE	t	R^2	ΔR^2
Step one: Academic subtests					
Quantitative Composite (MK+AR)	.171***	.041	4.83		
Reading Comprehension	.105**	.081	2.97	.055***	
Step(s) two: Spatial subtests					
Mechanical Comprehension	.143***	.092	4.08	.072***	.017***
Electric Maze	.061	.097	1.83	.058***	.004
Block Counting	.101**	.094	3.02	.064***	.009**
Rotated Blocks	.135***	.120	4.02	.071***	.017***
Hidden Figures	.080*	.108	2.39	.060***	.006*
Scale Reading	.156***	.060	4.28	.073***	.019***
Table Reading	.170***	.054	5.11	.081***	.027***

Note: Results presented in step two represent the second step of seven independent regression analyses; * $p<.05$, ** $p<.01$, *** $p<.001$

Hierarchical regression analyses were then performed to determine the incremental predictive validity of spatial ability and perceptual speed over traditional cognitive subtests on participant daily flight performance. In steps one, the quantitative composite and Reading Comprehension subtest were entered as predictors of daily flight performance. In step two, a single spatial ability or perceptual speed subtest was entered as an incremental predictor. This process was repeated for each seven spatial and perceptual speed AFOQT form Q subtests: Mechanical Comprehension, Electric Maze, Block Counting, Rotated Blocks, Hidden Figures, Scale Reading, and Table Reading. Results indicate all spatial and perceptual subtests except Electric Maze had significant incremental predictive validity for daily flight performance: Mechanical Comprehension [$\beta=.143$, $p<.0001$; $\Delta R^2=.017$, $p<0001$], Block Counting [$\beta=.101$, $p<.01$; $\Delta R^2=.009$, $p<.01$], Rotated Blocks [$\beta=.135$, $p<.0001$; $\Delta R^2=.017$, $p<.0001$], Hidden Figures [$\beta=.080$, $p<.05$; $\Delta R^2=.006$, $p<.05$], Scale Reading [$\beta=.156$, $p<.0001$; $\Delta R^2=.019$, $p<.0001$], and Table Reading [$\beta=.170$, $p<.0001$; $\Delta R^2=.027$, $p<.0001$] (Table 2.5).

2.10.2 Pilot Academic Performance

We once again examined optimal composition of five traditional AFOQT form Q subtests (Reading Comprehension, Verbal Analogies, Word Knowledge, Math Knowledge and Arithmetic Reasoning) that were predictive of pilot trainee academic performance. All five subtests were entered into a regression equation, and subtests were removed using a backward elimination approach, $p>.05$. As with daily flight performance, the optimal composition of predictors of pilot academic performance was a quantitative composite of Math Knowledge and Arithmetic Reasoning [$\beta=.302$, $p<.0001$] and the Reading Comprehension subtest [$\beta=.169$, $p<.0001$], F (2905) = 86.21, $p<.0001$, $R^2=.161$).

Hierarchical regression analyses were performed to determine the incremental predictive validity of spatial ability and perceptual speed subtests on pilot trainee academic performance. Traditional cognitive subtests (i.e., the quantitative composite and Reading Comprehension subtest) were entered into step one. In step two, spatial cognition subtests were entered as an additional incremental predictor; this process was repeated for each of seven AFOQT form Q spatial and perceptual speed subtests. Results demonstrate only subtests Mechanical Comprehension [$\beta = .161$, $p < .0001$; $\Delta R^2 = .022$, $p < .0001$] and Rotated Blocks [$\beta = .119$, $p < .001$; $\Delta R^2 = .013$, $p < .001$] provide incremental predictive validity over traditional cognitive aptitude subtests for trainee pilot academic performance.

2.11 Study Three Discussion: Spatial Cognition Incremental Validity

Despite previous factor analysis and structural equation modeling results demonstrating distinct differences between spatial ability and perceptual speed tests on the AFOQT (Carretta and Ree 1996; Drasgow et al. 2010), our factor analysis findings supports the approach of assessing tests as a single spatial cognition factor. This mirrors "Model 6" fitted in Carretta and Ree (1996) which specified AFOQT subtests for spatial ability and perceptual speed as one factor. While the authors ultimately chose a different factor structure separating the two constructs, they did not consider indices of parsimony/complexity in model fit and selection. Doing so would have likely favored the model with a combined spatial/perceptual speed factor. Furthermore, established research literature consistently conceptualizes perceptual speed and spatial ability as distinct yet related facets of overall spatial cognition (Carroll 1993; Fleishman et al. 1999; Fleishman and Quaintance 1984). Therefore we found it prudent to conceptualize these tests as distinct but related facets of overall spatial cognition constructs and examine the incremental validity of both perceptual speed and spatial ability subtests.

Interestingly, perceptual speed tests Scale Reading and Table Reading demonstrated the greatest incremental validity compared to other AFOQT spatial cognition subtests. In all, each spatial subtest with the exception of Electric Maze added significant, incremental predictive validity on participant daily flight performance. Considering the visual nature of executing maneuvers in both simulation and real-world flight situations on a daily basis (Barron and Rose 2013), increased spatial awareness/acuity and associated enhanced perceptual speed likely significantly improves daily trainee performance (Carretta et al. 1996).

In contrast, the pattern observed for daily flight was not repeated when predicting pilot academic performance. Only Mechanical Comprehension and Rotated Blocks demonstrated incremental validity. However, the Mechanical Comprehension subtest in AFOQT form Q often requires solving basic arithmetic problems in the context of mechanical systems. As a result, performance on this subtest would likely relate to quantitative, academic performance, supported by significant correlations between Mechanical Comprehension and Arithmetic Reasoning [$r = .37, p < .001$] as well as with Math Knowledge [$r = .26, p < .001$]. Rotated Blocks, in contrast, likely predicts pilot academic performance as Phase I of SUPT commonly makes use of paper-and-pencil scenarios to teach aviation basics like flying fundamentals, navigation, and other hypothetical situations requiring visualization and mental rotation of self and aircraft (Barron and Rose 2013; O'Neil and Andrews 2000). Classroom instruction reliant on visualization-related mental rotation and spatial orientation would favor those with heightened spatial abilities, especially in situations where they lacked domain-specific expertise (Ackerman 1988; Hambrick et al. 2011; Hambrick and Meinz 2011; Uttal et al. 2012).

2.12 Discussion

In this chapter we presented military aviation as an important exemplar of a STEM field in which many individuals without prior domain-knowledge must be trained to perform effectively each year. We began comparing and contrasting traditional (verbal, quantitative) and non-traditional (spatial ability, perceptual ability, specialized knowledge) tests of cognitive aptitude via exploratory factor analysis. We also examined similarities between spatial ability and perceptual speed, opting to combine them into a single spatial cognition factor. We then examined the predictive validity of spatial ability measures relative to traditional academic admissions tests involving quantitative and verbal abilities. Our meta-analysis replicates examinations of success in other STEM fields (Uttal and Cohen 2012; Wai et al. 2009) in showing that quantitative aptitude was consistently a better predictor of pilot training outcomes than verbal aptitude. Results show traditional academic aptitude tests are generally somewhat stronger predictors of pilot training outcomes than spatial tests. Across multiple studies, meta-analysis results show quantitative tests [$\rho = .334$] were substantially stronger predictors of purely academic pilot training outcomes than perceptual speed [$\rho = .286$] or spatial tests [$\rho = .227$]. In contrast, perceptual speed [$\rho = .218$] was only a marginally better predictor of practical, "hands on" flight training outcomes compared to quantitative [$\rho = .182$] and spatial ability tests [$\rho = .153$]. Considering academic instruction is frequently the foundation of future hands-on training in military aviation (Carretta and Ree 1995; O'Neil and Andrews 2000), organizations choosing a single type of screening might view the content of traditional aptitude testing as sufficient.

However, considering the dual academic and "hands-on" nature of military pilot training, the choice of whether to screen candidates on academic (quantitative) or spatial measures should not be an "either or" conundrum—rather, by combining academic and spatial measures, we suggest organizations are most likely to identify those individuals who not only have the aptitude to excel, but also have the supplemental spatial aptitude to grasp critical STEM concepts in applied fields like military aviation. Hence, study three demonstrates the substantial incremental validity of spatial cognition (spatial ability and perceptual speed) subtests for predicting both hands-on and academic pilot training outcomes.

2.12.1 Present and Future Challenges to Spatial Abilities Testing: Recommendations

While benefits of selecting for spatially gifted candidates are readily apparent, present and future challenges exist for increasing use of spatial abilities testing for selection and classification purposes. One critical challenge is reducing or minimizing adverse impact to female candidates. Science, technology, engineering, and mathematics fields already suffer from persistent under-representation of women in STEM fields (Ceci et al. 2009; Halpern 2012; Wai et al. 2009), compounded by significant sex differences in performance on spatial abilities measures (Linn and Peterson 1985). While some disparity may be attributed to physiological differences between sexes, still others are the result of cultural, societal, and educational differences between the treatment of male and female students (Miller and Halpern 2013; Syzmanowicz and Furnham 2011). Finally, significant differences in adverse impact exist even among subtests (Barron and Rose 2013; Linn and Peterson 1985; Miller and Halpern 2013). Assembling Objects (AO), the only spatial subtests on the Armed Services Vocational Aptitude Battery (ASVAB), is not used for selection purposes by any branch of the US military. Currently only the Navy uses AO for occupational classification (Held and Carretta 2013). However, Barto et al. (2014) recently suggested adding AO or replacing the ASVAB Mechanical Comprehension subtest in several mechanical-oriented Air Force occupational qualification composites to improve predictive validity and reduce adverse impact.

Specific recommendations to reduce gender inequality from a selection standpoint is to (1) determine the occupational necessity of using spatial abilities testing as selection criteria (i.e., military aviation), (2) select for spatial abilities that serve as significant predictors of performance while minimizing adverse impact (Barron and Rose 2013), (3) identify spatial ability *tests* and *procedures* that maximize predictive validity while minimizing adverse impact (Barron and Rose 2013; Linn and Peterson 1985; Miller and Halpern 2013), and (4) provide opportunities for spatial training for both sexes with deficient spatial ability that are otherwise occupationally qualified.

The concept of training “ability” may at first seem counterintuitive as abilities are seen as relatively immutable compared to knowledge and skills. However, evidence shows the use of spatial training can significantly improve spatial ability, and spatial training on specific spatial abilities generalizes to other spatial abilities (Uttal et al. 2013). For example, the use of spatial training to improve mental rotation of three-dimensional objects significantly improved engineering student spatial ability and success of degree obtainment (Sorby 2009). While spatial training can include activities as simple as paper folding (Newcombe 2010) or using popular two-dimensional games like Tetris (Uttal et al. 2013), the incorporation of technology and augmented reality may be key in providing cost-effective, beneficial spatial training to adolescents and adults (Martin-Gutierrez et al. 2010). Considering spatial abilities are critical predictors of STEM success absent domain-specific knowledge (Ackerman 1988; Hambrick et al. 2011; Hambrick and Meinz 2011; Uttal and Cohen 2012), identification and use of spatial training to improve spatial abilities of otherwise qualified candidates provides organizations both a larger applicant pool and a progressive approach to reducing disparity among males and females in STEM fields. Even when disparity between male and female spatial abilities persist post-training, both groups demonstrate improvement to the degree other skills and abilities predicting success in STEM fields like persistence, communication, and creativity become salient (Newcombe 2010).

A final challenge for spatial abilities testing and organizations are that occupations are becoming increasingly integrated with and reliant upon sophisticated technology. Specific to military aviation is the increased use of remotely-piloted aircraft (RPA) for both combat and non-combat roles. The US military has increased number of daily RPA flights steadily for over a decade, with a projected 50 % increase in daily RPA flights by 2019 (Lubold 2015). While advantages of RPA include increased surveillance and reconnaissance capabilities along with reduced risk of pilot casualty, it comes at a cost of requiring pilots to make critical decisions absent spatial information traditionally gained being physically in a cockpit. Piloting from a remote location requires specific spatial acuity to manipulate spatial forms in three-dimensions based on data from two-dimensional screens. Furthermore, RPA pilots must interpret velocity, altitude, and other flight characteristics without the benefit of physical feedback (Tvaryanas 2006). As technology matures it is expected that RPAs will become more automated and autonomous, requiring less emphasis on flying skill and more emphasis on supervisory control and operator-RPA (i.e. human-machine) team functioning (Carretta et al. 2007). Increased automation and autonomy may enable a single pilot to supervise multiple systems. In such a scenario cognitive ability and job knowledge will likely remain important. However, contingent on the effects of automation and supervisory or active pilot-operator roles, specific spatial ability requirements may increase (e.g., perceptual speed) while others decrease.

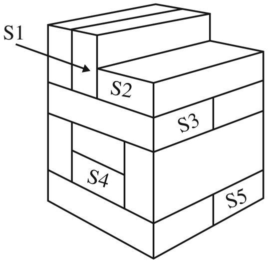
This concept of physical versus virtual “presence” (see Wirth et al. 2007) is not limited to military aviation – how STEM fields rely on and make use of technology will ultimately determine how (and whether) spatial abilities testing continues to predict STEM field success. Therefore the field and science of spatial abilities testing must continue to develop methods of assessment that accurately reflect how spatial ability is used within technology-dependent STEM fields. Furthermore, organizations must remain cognizant of the benefit of spatial abilities testing while acknowledging changing job roles and reliance on technology will alter how spatial abilities predict occupational performance.

2.12.2 Limitations

Some limitations of the studies in this chapter should be noted. First, because the purpose of this chapter was to examine incremental predictive validity of spatial cognition beyond traditional cognitive aptitude tests, we did not include aviation-specific knowledge variables in either our factor analysis or incremental validity analyses. Although military aviation and training frequently involves applicants with little or no prior aviation experience (Dickinson 2012; Hunter and Burke 1994), future examination similar to ours should consider including prior knowledge as an additional predictor or covariate. Second, despite our attempts to minimize the impact of training differences, the use of a sample training on two distinctly different aircraft (T-37 vs. T-6) likely introduced some degree of error into our findings. Finally, we examined the incremental validity of seven spatial subtests individually, avoiding attempts at model building to focus on the comparative incremental validity of multiple spatial cognition subtests. Future studies should extend findings to determine which combination of spatial cognition tests would maximize incremental predictive validity over traditional tests of cognitive aptitude.

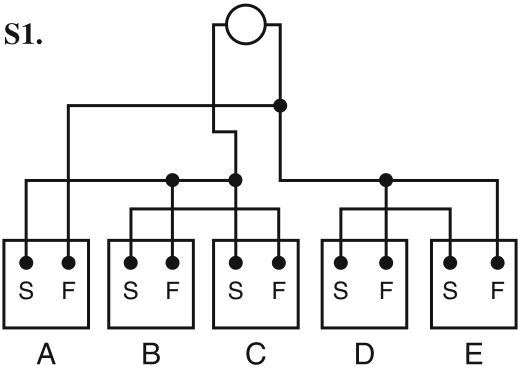
Appendix A: Spatial Subtest Item Examples

Block Counting:

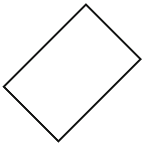


KEY					
Block	**A**	**B**	**C**	**D**	**E**
S1	1	2	3	4	5
S2	3	4	5	6	7
S3	5	6	7	8	9
S4	2	3	4	5	6
S5	2	3	4	5	6

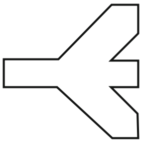
Electrical Maze:



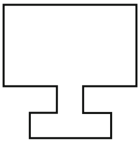
Hidden Figures:



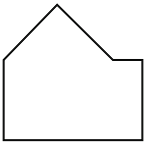
A



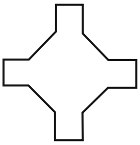
B



C

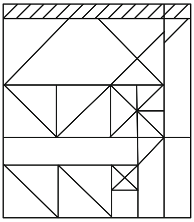


D

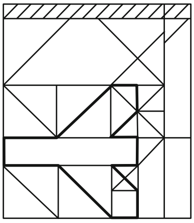


E

The numbered drawings are similar to drawing X below. Which one of the five figures is contained in drawing X?

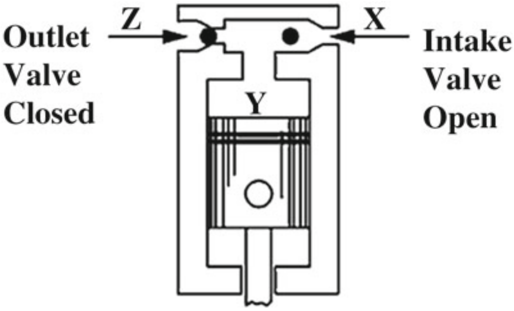


X



Y

Mechanical Comprehension[1] (*ASVAB Exemplar*):



Why does the intake valve open on this pump when the piston goes down?

(A) Air pressure at X is less than air pressure at Y.
(B) Air pressure at Z is less than air pressure at X.
(C) Air pressure at X is greater than air pressure at Y.
(D) Air pressure at Y is greater than air pressure at Z.

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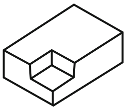
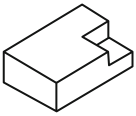
[1] *Source:* http://official-asvab.com/questions/app/question_mc3_app.htm

Rotated Blocks:

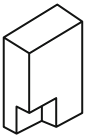
S1



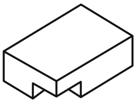
A



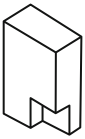
B



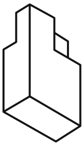
C



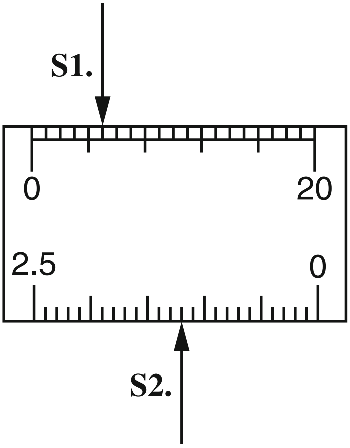
D



E

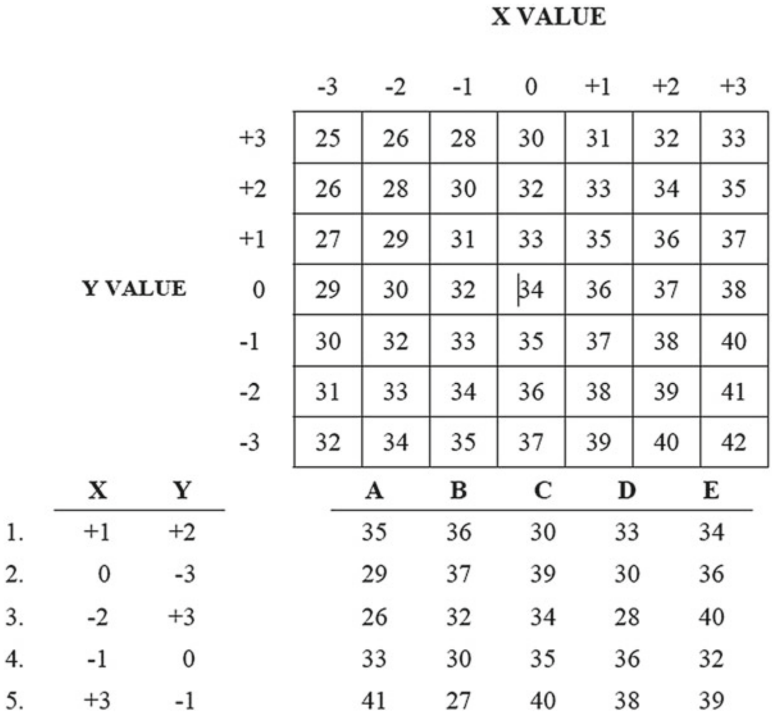


Scale Reading:



S1.	**A**	6.00
	B	5.00
	C	4.25
	D	2.25
	E	1.25
S2.	**A**	13.0
	B	12.0
	C	10.2
	D	1.3
	E	1.2

Table Reading:



X VALUE

		-3	-2	-1	0	+1	+2	+3
	+3	25	26	28	30	31	32	33
	+2	26	28	30	32	33	34	35
	+1	27	29	31	33	35	36	37
Y VALUE	0	29	30	32	34	36	37	38
	-1	30	32	33	35	37	38	40
	-2	31	33	34	36	38	39	41
	-3	32	34	35	37	39	40	42

	X	**Y**	**A**	**B**	**C**	**D**	**E**
1.	+1	+2	35	36	30	33	34
2.	0	-3	29	37	39	30	36
3.	-2	+3	26	32	34	28	40
4.	-1	0	33	30	35	36	32
5.	+3	-1	41	27	40	38	39

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Chapter 3
Spatial Ability: Measurement and Development

Rita Nagy-Kondor

3.1 Definition of Spatial Ability

Spatial visualization skills are very important to success in several disciplines. Spatial thinking has an important role in the teaching and learning of mathematics process. Many studies have shown that there are correlations between various measures of spatial skills and performance in particular Science, Technology, Engineering and Mathematics (STEM) disciplines (Uttal and Cohen 2012). According to previous studies students with high scores on a mental rotation test systematically score higher on anatomy examinations (Vorstenbosch et al. 2013). Studies showed that this ability has positive correlations with geometry and mathematics education (Bosnyák and Nagy-Kondor 2008). Spatial visualisation ability is a predictor for success in technical education, spatial ability development is very importance in engineering training, especially for architects (Ault and John 2010; Langley et al. 2014; Leopold et al. 2001; Nagy-Kondor 2008a, 2014; Nagy-Kondor and Sörös 2012; Nagy-Kondor and Szíki 2012). Spatial ability is an ability indispensable for cultivate hundreds of professions and vocations (Séra et al. 2002). The skills needed to develop a person's spatial ability are acquired through programs or activities that teach engineering or drafting (Olkun 2003). In addition, Shea et al. (2001) state that the intellectually talented adolescents who has better spatial than verbal abilities are more likely to be found in the field of engineering, computer sciences and mathematics. As a result, great attention has been given to spatial ability by STEM field educators. Correlations between various spatial measures and STEM outcomes are significant (Uttal and Cohen 2012), and often quite strong.

Authors define spatial ability in different ways, but they all agree that it is a complex ability, that connects the perceived and constructive 3D world.

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Gardner (1983) distinguishes between seven different types of intelligence: linguistic, logical-mathematical, spatial, musical, physical-kinesthetic, interpersonal and intrapersonal. According to Gardner (1983, p. 9) the “spatial intelligence is the ability of forming a mental model of the spatial world and maneuvering and working with this model”. Spatial visualization can be defined as the abilities of imagine the visualization of an object from different viewpoints, rotation of it and blend or integrate of the parts of the given object (Haanstra 1994; McGee 1979; Olkun 2003).

Linn and Petersen (1985, p. 1484) in a meta-analysis article, maintain spatial ability into three categories; spatial perception, spatial (mental) rotation and spatial visualization. According to them, spatial perception is a kind of spatial ability that requires a subject to determine spatial relationships with respect to the orientation of their own bodies, in spite of distracting information; spatial (mental) rotation is a kind of ability that requires a subject to rotate a two-dimensional or three dimensional figure rapidly and accurately; spatial visualization is a kind of spatial ability that requires the subject to demonstrate an ability that involves complicated, multi-step manipulations of spatially presented information.

McGee (1979) defines spatial ability as “the ability to mentally manipulate, rotate, twist or invert pictorially presented stimuli”, McGee (1979) and Maier (1998) classify five components of spatial skills as

- Spatial perception: the vertical and horizontal fixation of direction regardless of troublesome information;
- Spatial visualization: it is the ability of depicting of situations when the components are moving compared to each other;
- Mental rotation: rotation of three dimensional solids mentally;
- Spatial relations: the ability of recognizing the relations between the parts of a solid;
- Spatial orientation: the ability of entering into a given spatial situation.

Séra et al. (2002) are approaching the spatial problems from the side of the activity. The types of exercises:

- projection illustration and projection reading: establishing and drawing two dimensional projection pictures of three dimensional configurations;
- reconstruction: creating the axonometric image of an object based on projection images;
- the transparency of the structure: developing the inner expressive image through visualizing relations and proportions;
- two-dimensional visual spatial conception: the imaginary cutting up and piecing together of two-dimensional figures;
- the recognition and visualization of a spatial figure: the identification and visualization of the object and its position based on incomplete visual information;
- recognition and combination of the cohesive parts of three-dimensional figures: the recognition and combination of the cohesive parts of simple spatial figures that were cut into two or more pieces with the help of their axonometric drawings;

- imaginary rotation of a three-dimensional figure: the identification of the figure with the help of its images depicted from two different viewpoints by the manipulation of mental representations;
- imaginary manipulation of an object: the imaginary following of the phases of the objective activity;
- spatial constructional ability: the interpretation of the position of three-dimensional configurations correlated to each other based on the manipulation of the spatial representations;
- dynamic vision: the imaginary following of the motion of the sections of spatial configuration.

According to Linn and Petersen (1985, p. 1982), spatial reasoning refers to the skill in representing, transforming, generating and recalling symbolic nonlinguistic information. Another definition on spatial reasoning expressed by Williams et al. (2010, p. 2) as the ability concerned with the representation and use of objects and their relationships within a world conceived of both topologically and geometrically in two and three dimensions, with or without time as a fourth dimension.

One of the factors effecting spatial ability is age. Spatial ability has surfaced a salient characteristic of young adolescents who go onto develop expertise in science, technology, engineering, and mathematics (STEM) (Lubinski 2010). Piaget and Inhelder (1967) have categorized the development of spatial cognition into four stages based on age, where at the formal operational stage from age 13 onwards a child is capable of exploring mental manipulation involving infinite spatial possibilities and complex mathematical concepts (cited in Rafi et al. 2005, p. 708). Results of meta-analyses (Linn and Petersen 1985; Voyer et al. 1995) showed, although the amount of difference varies by the age of the group taking mental rotation tests, males tend to outperform females on mental rotation at any age starting with age 10, at which the earliest measurement of mental rotation was possible (Yılmaz 2009, p. 90). Voyer et al. (1995) expressed, that difference before age 18 is not significant in spatial visualization, while the difference is significant over the age 18. Lubinski (2010) suggest that individuals who go onto achieve educational and occupational credentials in STEM tend to be distinguished by salient levels of spatial ability, relative to verbal ability during early adolescence.

Several studies have indicated that there are various factors effecting spatial ability; one of factor is gender. According to Tsutsumi et al. (1999) females are much less likely to get high scores in Mental Cutting Test. In general, boys have a higher spatial ability than girls which may be caused by biological and/or environmental factors (Yılmaz 2009, p. 93). And the related literature shows that there is a significant male advantage on mental rotation tasks at every age (Linn and Petersen 1985; Pietsch and Jansen 2012; Voyer et al. 1995). According to Linn and Petersen (1985) and Voyer et al. (1995) the factor of spatial visualization also shows a male advantage. Yet, the difference between males and females on those tests are much smaller than those found in the mental rotation and spatial perception (Yılmaz 2009, p. 90). There are conflicting results in the reviewed literature; for instance, (Turgut and Nagy-Kondor 2013b) found that there is not a significant difference between male and female groups' scores in spatial visualization of prospective elementary mathematics teachers. Due to these conflicting results the educators are still interested in gender difference in case of spatial ability.

3.2 Measurement of Spatial Ability

It is very important to detect early the students with lower levels of spatial ability, because later will be negative impact by studies. The past 15–20 years increased the number of researches, that the engineering (or other) students are aimed for the development of spatial ability. The components of spatial ability necessary most accurate to measure. The measurement of spatial abilities is standardized by international tests, among which the Mental Cutting Test (MCT) and Mental Rotation Test (MRT) is of greatest importance. MCT presents a 3D object with an imaginary cutting plane and five possible solutions for the cross-section shape. MRT presents a criterion figure shown along with four candidate figures, two of which represent the criterion figure in a rotated position. Heinrich Spatial Visualization Test (HSVT), Purdue Spatial Visualization Test (PSVT) and Purdue Spatial Visualization Test – Visualization of Rotation (PSVT-R) are widely used for testing the spatial ability.

Much work has been reported an analysis of MCT (Ault and John 2010; Leopold et al. 2001; Tsutsumi et al. 1999; Turgut and Nagy-Kondor 2013a), MRT (Ault and John 2010; Leopold et al. 2001; Pietsch and Jansen 2012; Rafi et al. 2006; Shiina et al. 2001), HSVT (Heinrich 1989; Turgut and Nagy-Kondor 2013b) and PSVT-R (Ault and John 2010; Ferguson et al. 2008; Sorby 2001; Sorby et al. 2014; Scribner 2004) results of engineering students or prospective mathematics teachers. Most US and United Arab Emirates researchers have used the PSVT-R to measure visualization skills; MCT and MRT is widely used in Europe and Japan.

The standard MCT (a sub-set of College Entrance Examination Board [CEEB] 1939) was first developed for university entrance exam in the USA. MCT consists of 25 items. In each item presents a three dimensional object which is to be cut with an assumed cutting plane in perspective projection, and five alternative views of the resulting section (one correct alternative and four incorrect alternatives), resulting from the cut. The students is required to choose the single view that represents the correct section. Example item of the test is given in Fig. 3.1 (Németh and Hoffmann 2006). It was shown by Saito et al. (1995) and Tsutsumi et al. (1999) that in order to

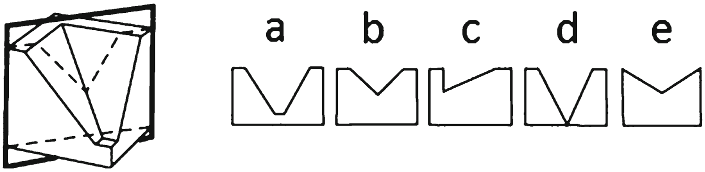
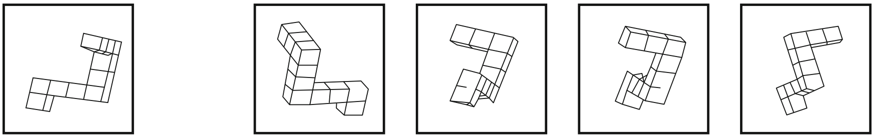


Fig. 3.1 Example item for MCT



The Target Item Alternatives

Fig. 3.2 MRT example problem

solve the MCT problems, subjects go through three phases of information processing, which are:

- Recognizing the solid from the perspective drawing,
- Cutting the solid by the assumed cutting plane,
- Judging the characteristic quantity of the section, if necessary.

MRT is introduced by Vanderberg and Kuse (1978). MRT is consisted of 20 questions. 2D representation of a 3D object composed of cubes is shown when seen from one angle. Each item consists of five stimuli, which include a target that consists of three-dimensional cubes and four alternatives (see Fig. 3.2) (Turgut 2015). Each problem is composed of a criterion figure, two correct alternatives and two incorrect alternatives. Correct alternatives are structurally identical to the criterion, but shown in a rotated position. The subjects are asked to find the two correct alternatives.

One of paper-and-pencil test is HSVT. This test was developed by Heinrich (1989) to examine the spatial abilities of engineering graphics students. The original HSVT includes two major expert skills in spatial visualization: synthesis and decomposition. For each two basic skills she hypothesized that when mental rotation was added to these tasks at three hierarchical levels of complexity, this would render the spatial problem solving progressively more difficult (Chen 1995, p. 2).

The original HSVT consists of 48 items divided into 6 scales:

- synthesis without rotation;
- decomposition without rotation;
- synthesis with one-step rotation;
- decomposition with one-step rotation;
- synthesis with two-step rotation;
- decomposition with two-step rotation.

Example items of the test are given in the following figures.

Figure 3.3 expresses an example about the part of “Synthesis”. Synthesize four pieces, adjusting Probe X to fit piece first and selecting one of five options A, B, C, D, E to replace the question mark (Chen 1995, p. 3; Heinrich 1989).

In the Fig. 3.4, decompose given pattern three pieces, X + ? + Y, where probes X,Y may need to be adjusted, and after selecting one of five options, A, B, C, D, E to replace the question mark. The reduced test includes 15 items for the part of “synthesis”, and 10 items for the part of “decomposition”.

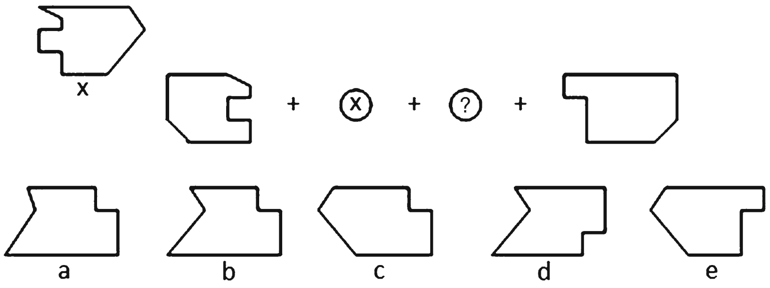


Fig. 3.3 Example item for synthesis section

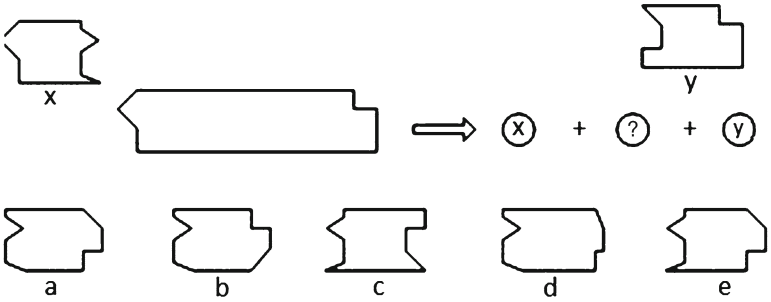


Fig. 3.4 Example item for decomposition section

Guay (1977) developed the PSVT in 1976 to determine student's ability to visualize, recognize orthograpic drawings. The PSVT includes three sections: developments (identification of the figure), object rotations and views.

Most researchers use only the object rotations portion (PSVT-R). The rotations section shows an object in two different positions. The first object is rotated on the X, Y or Z-axis, to show the rotation pattern. A second object is presented with five alternative views, one represents the second object subjected to the same rotation as the example. Coordinate axes were added to the first and second stimulus objects, but they were not added to the five solution choices (Branoff 1998; Branoff and Connolly 1999). The first stimulus object was shown in its new, rotated position. Figure 3.5 expresses an example about the part of PSVT-R (with coordinate axes) (Branoff and Connolly 1999).

In general, the average scores of PSVT-R are consistently reported to be around 75 % across US 4-year engineering universities; many other studies report similar data among engineering students. Average scores around 62 % for MRT are comparable for universities in the US, Poland and Germany, with slightly higher scores in Brazil and Malaysia. Results of the MCT are comparable with an average around 60 % for universities in the US, Australia and Europe (Ault and John 2010; Ferguson et al. 2008; Field 1999; Gorska and Sorby 2008; Leopold et al. 2001; Rafi et al. 2006; Seabla and Santos 2008; Sorby 2001) Spatial visualization skills of entering first year engineering students at the Polytechnic of Namibia are significantly lower

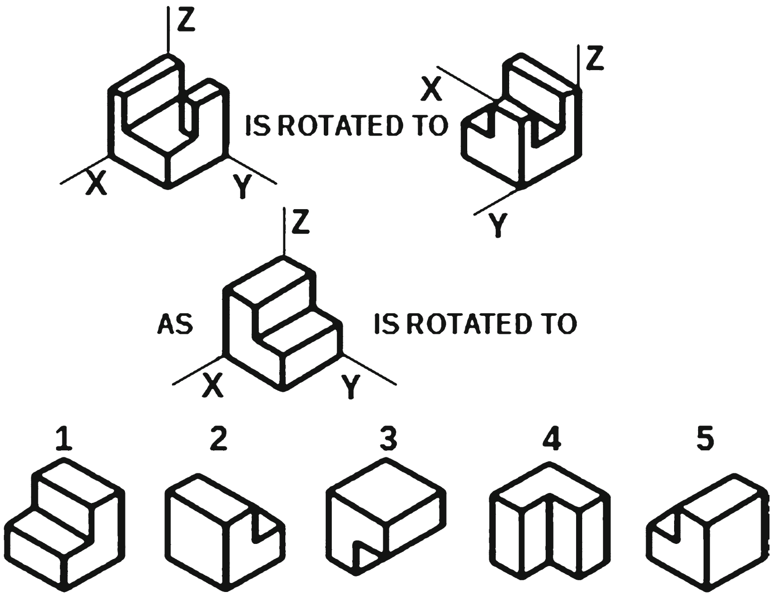


Fig. 3.5 Example item for PSVT-R

than those of most students in industrialized countries, but comparable to cohorts of minority engineering students in the US. Ault and John (2010) hypothesize that these differences are due to factors of prior experience and educational background.

These are the most commonly used spatial tests. There are testing procedures, which break with tradition paper pencil basis testing: testing with computer. By dynamic testing it is important to consider whether we measure what we would like really beside the given conditions.

3.3 Development of Spatial Ability

Given the contemporary push for developing STEM talent in the information age, an opportunity is available to highlight the psychological significance of spatial skills (Lubinski 2010). Development of spatial ability by the aid of Information and Communication Technologies had great attention in the reviewed literature, especially with Dynamic Geometry Systems (Clark and Scales 2000; Kurtulus 2013; Nagy-Kondor 2008b, 2010). Studies suggest that computer, interactive animation and virtual solids are promising tools for training spatial thinking, and we can achieve better results in mathematics classes with the use of Dynamic Geometry Systems (Budai 2013; Gerson et al. 2001; Kurtulus 2013; Martín-Gutiérrez et al. 2013; Nagy-Kondor 2008a, b; Sorby 2001; Yue 2009). Using engineering and Dynamic Geometry applications makes the connection between mathematics and

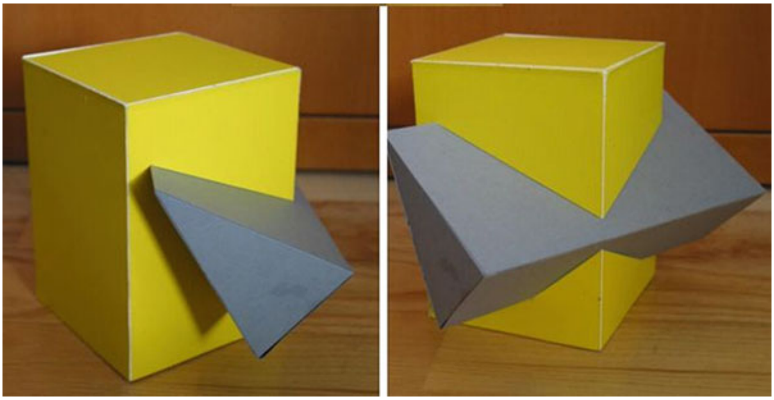


Fig. 3.6 Traditional concrete models: intersection of solids 1 (Papp)

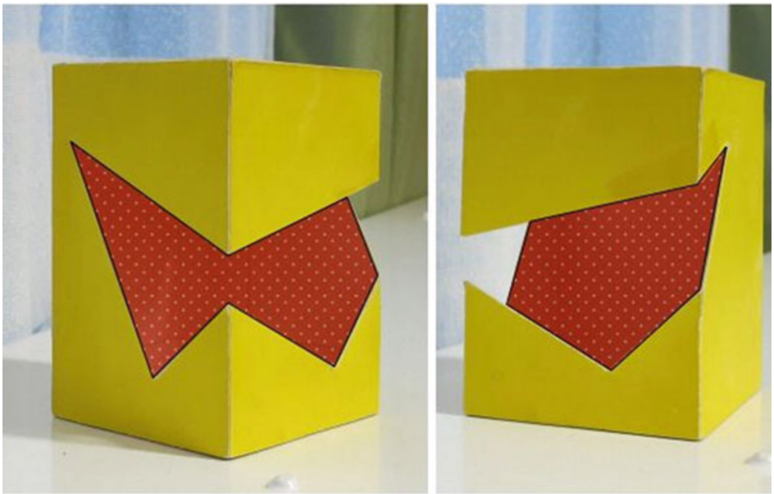


Fig. 3.7 Traditional concrete models: intersection of solids 2 (Papp)

the special engineering subjects clearer for the engineering students. Besides their use in education the GeoGebra or other Dynamic Geometry applications can be useful tools in different engineering fields like dynamic model calculation of alternative drive vehicles, useful help for example for designers of pneumobiles (Szíki et al. 2014). GeoGebra or other Dynamic Geometry animations help the students to understand the engineering content and also its relationship with the mathematical content and develop the spatial ability.

Traditional concrete models are very useful to develop spatial ability; it is important to use computer not instead of but rather, alongside them (Figs. 3.6 and 3.7).

Models and toys that help children develop spatial ability and creativity: construction toys, building blocks (Legos, spatial models), puzzles, origami, board games.

Fig. 3.8 Kubus – a spatial ability development tool

Kubus is one of the useful approach to spatial ability development tool, especially to projection illustration and projection reading (http://armarium.hu/kubus.php) (Fig. 3.8). The inventor is Á. Endre Pattantyús. He was a mechanical engineer teacher. Kubus was once a "authorized by the Minister teaching tools" in Hungary.

Let see some research experiment, some examples in subject of spatial ability, only some from the more interesting ones (with the use of Dynamic Geometry Systems and/or with traditional mathematics tools).

Lord (1985) applied a 30 min practice on a 14 weeks course with first/second year students where they had tasks in which they had to cut three-dimensional solids in their mind and then they had to draw the surface of the two-dimensional planes they got. In the post-test the spatial awareness and efficiency became better.

Field (1999) describes work conducted at Monash University aimed at measuring spatial skills, improving the sensitivity of visualization tests, and developing the skill for some engineering undergraduates. The testing of undergraduate students at Monash University has indicated the following factors:

- First level engineering students are to possess specially higher spatial skills than the general population.
- Spatial skills are not measurably developed by a conventional mechanical engineering undergraduate course.

A special course with about 50 contact hours appears to have been successful in developing visualization skill in first level engineers. (There is some evidence that freehand drawing of three dimensional objects, in orthogonal, isometric and perspective views makes a major contribution to the development of spatial skill.)

GeoGebra was designed to combine features of dynamic geometry software (e.g. Cabri Geometry, Cinderella, Geometer's Sketchpad) and computer algebra systems (e.g. Derive, Maple) in a single, integrated system for teaching and learning mathematics; we can work in more than one window at the same time.

Algebra window contains the equations of the selected objects and both a plane worksheet and a spatial worksheet are displayed. We can work in these windows simultaneously. If we change a feature in one window it dynamically changes in the other windows (Hohenwarter and Preiner 2007). We can choose from a variety of projections. We can select how we would like to display the spatial object in a plane (parallel projection, axonometries). "Version 4.2 of GeoGebra does not include the display of spatial objects, but after defining one's own base system it is possible to display such objects. Version 5.0 Beta is still undergoing significant development, and under certain conditions its operation may therefore be unstable. Taking all of this into consideration, the best solution is to become familiar with both versions." (Budai 2013).

The use of computer expands the circle of mathematical problems to be raised in the classroom. Budai (2013) combined with plane space analogies for the development of spatial ability and problem-solving skills in the three dimensions of solid geometry. He presented the plane and spatial analogues of coordinate geometry with the help of GeoGebra, since part of the concept of this software is to show the algebraic and geometric view of the objects in parallel. His experience indicates that there is great promise for use of geometry programs, dynamic geometry system combined with plane space analogies. We can use analogies to solve several of mathematical problems together and understand the relationships between different sets of problems. From Budai's examples (Budai 2013) we can see how to create analogies in different ways in geometry, and many analogies can be found in secondary school material. The analogue features are clearly visible in the figure and the students can independently read the major theorems. Using the worksheet, the plane and spatial geometric windows were connected; if we move the straight line of the plane figure, the plane of the spatial figure moves at the same rate.

Plane-space analogies in public secondary education (within the framework of the mathematics curriculum) (Budai 2013):

- definition of the concept of planar and spatial objects, their mutual position and their distance (for example the distance of two straight lines and the distance of two planes or the distance of two lines not in the same plane)
- geometric transformations in the plane and space
- loci (for example the perpendicular bisector of a segment in the plane and in space, circle, sphere; from the circle-sphere analogues: similarity points, Apollonius-type problems, inversions, the power of a point concerning circles and spheres, lines of circles, lines of spheres, circle crowds with one parameter and their spatial analogue)
- application of angle functions in two dimensions and three dimensions (triangle and spherical triangle)

Figure 3.9 shows a possible GeoGebra adaptation of inversion. Figure 3.10 shows examination of calculation of the extreme value.

Fenyvesi et al. (2014) suggest that origami-based instructions are positive effect on spatial visualization, the combined approach connected hands-on activity with computer-based learning. By the combination of different experience-centered

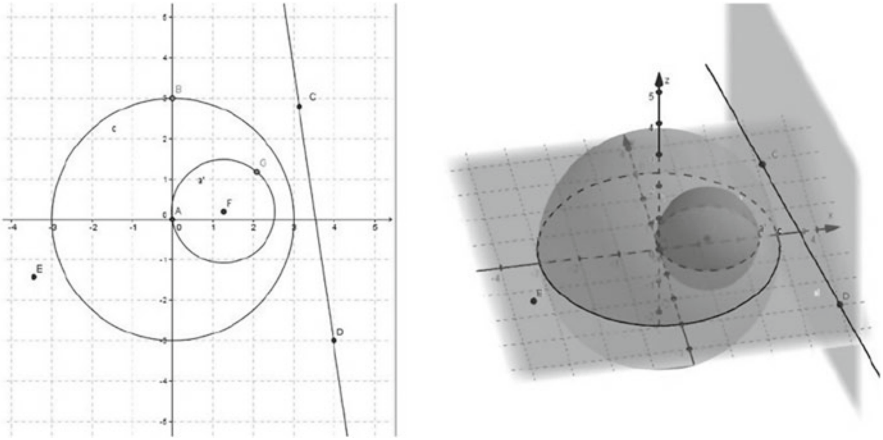


Fig. 3.9 Plane and spatial analogues of inversions (Budai 2013)

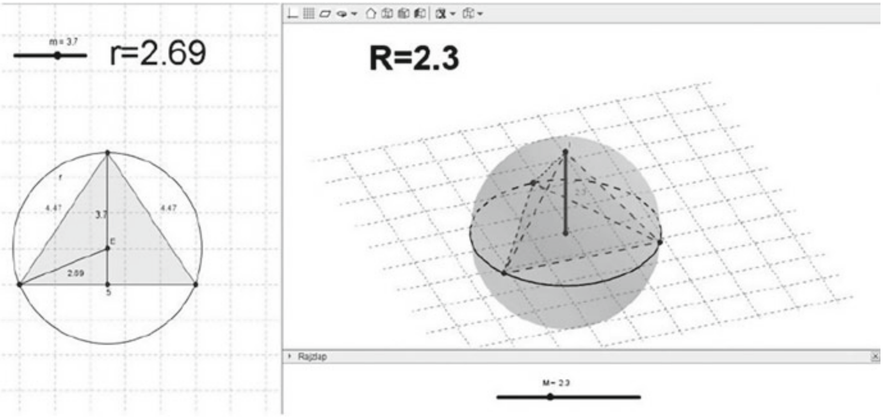


Fig. 3.10 Extreme value calculation (example of searching for and solving simple analogue problems) (Budai 2013)

approaches, students can improve their skills, spatial abilities in reasoning in various contexts. While making origami requires following certain procedures in paper folding GeoGebra allows the students to create a set of procedures that will lead to the solution. Both approaches illustrate real-world application of mathematical knowledge and bring abstract and difficult geometrical notions and thinking closer to the students. The fold origami diagrams and the interactive visualizations with GeoGebra might give an opportunity to make transitions from visual to formal statements. Due to their visual and interactive nature, origami and GeoGebra might enable students to see connections in the geometric statements more easily compared to students who receive standard instruction. Origami and GeoGebra solutions of the problem requires that the students recognize the epistemological limits of Euclidean geometry, to change perspective and experiment with new approaches (Fenyvesi et al. 2014). The origami-based instruction might contribute to students performing higher in achievement tests, like PISA as well (Arıcı and Aslan-Tutak 2013).

Takaci et al. (2014) used packages Mathematica and GeoGebra for the geometry constructions of illusions to analyse mathematical modelling processes of different illusions in a view of new technology. Starting from illusions as real problems, all stages, transitions from one stage to another are considered. Cognitive activities following the whole process of mathematical modelling of illusions are analysed. Interactive animations are the subject of numerous studies confirming their great challenge and positive impacts on education. Mathematical modelling connects mathematics with the real world problems. It is very important to analyse all cognitive activities following mathematical modelling process in teaching (Takaci et al. 2014).

Let see some examples of spatial tasks on the internet (rotation, projection illustration).

"Rotate the building until you get the right side view." You get 20 questions about buildings consisting of cubes. For each situation you have to find the correct view. You can rotate the building until you get the right view (Freudenthal Institute, Utrecht University) (http://www.fisme.science.uu.nl/toepassingen/03378/).

"Build small cubical houses by using an empty plane and then building up or by using a 'full' plane and then breaking down. You can look at your building from different directions and even rotate it with your mouse." (Freudenthal Institute, Utrecht University) (Boon; http://www.fisme.uu.nl/toepassingen/00249/toepassing_wisweb.en.html).

One of the good power to develop spatial thinking is shadow construction. Figure 3.11 shows, how can we construct the shadow (self-shadow (shade) and projected shadow) of the conic in Monge projection (with parallel lighting) with the help of GeoGebra (Németh). If we change a feature in one window (Monge projection) it dynamically changes in the other window (axonometric projection).

Descriptive Geometry provides training for students' intellectual capacity for spatial perception and it is therefore important for all engineers, physicians and natural scientists. "Descriptive Geometry is a method to study 3D geometry through 2D images thus offering insight into structure and metrical properties of spatial objects, processes and principles" (Stachel 2004, p. 327). Moreover some basic differential-geometric properties of curves and surfaces and some analytic geometry are included and one aim is also to develop the students' problem solving ability (Stachel 2004). The methods of descriptive geometry are based on projection. There are two basic types of projection: central and parallel projection (if the rays of the projection are orthogonal to the projection plane, then the projection is called orthogonal projection). Gaspard Monge – the founder of descriptive geometry – first developed his techniques (called Monge projection) to solve geometric problems in 1765 while working as a draftsman for military fortifications (Carlbom and Paciorek 1978). Orthogonal projections onto two orthogonal planes are the basis of this method. Monge projection is very important in engineering.

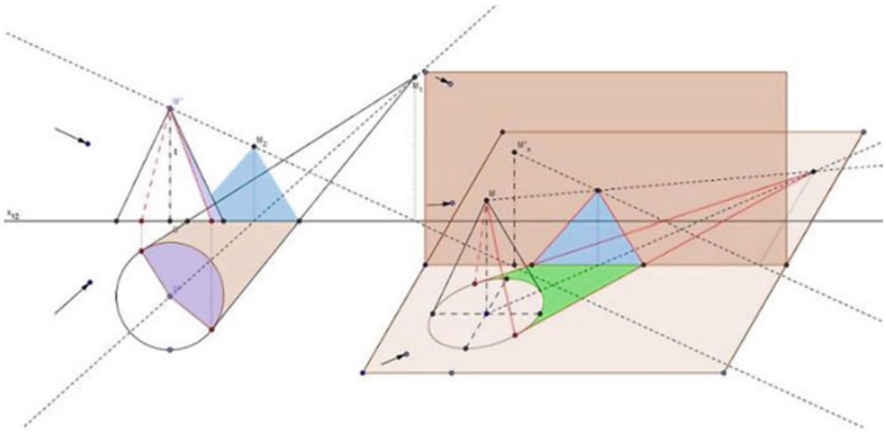
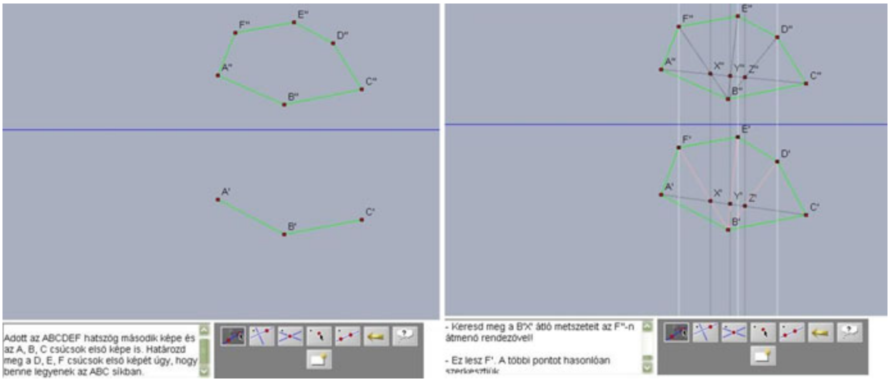


Fig. 3.11 Shadow of conic (Németh n.d.)

Types of problems in Descriptive Geometry: Incidence and intersection problems, shadow constructions; Metrical constructions; Representation of spatial elements, polyhedrons, circle, sphere, cylinder and cone. Methodology: Multi-view representation, auxiliary projections; Axonomety; Perspective. The most important ability in working with Descriptive Geometry is spatial ability.

In order to support teaching Descriptive Geometry, there are some topics of secondary school geometry: Basics of representation (Distance and angels of space elements, perpendicularity. Remarkable set of points. Conic sections. Categorize of polygons. Regular polygons. Basic Euclidean constructions. Projection, reconstruction.) Plane and space geometry (Measure of the angle. The geometry of triangles (relations between the sides and angles). The geometry of circles. Area and perimeter of plane figures, volume and surface area of space figures. Determination of the geometric parameters of plane and space structures. Calculation of the surface area and mass of solid plates and bodies.) Coordinate geometry (Distance between points. Angle between vectors. Proportional division of a line segment. Centroid of a triangle, centre of gravity of a system of particles. Functions of plane curves (line, circle, ellipse, parabola). Calculation of the intersection points of plane curves).

Understanding is one of basic conditions of effective study. According to Skemp (1971), understanding something is equal to assimilating it with an appropriate "scheme" (conceptual structure). The sufficient inner organization of the definitional structure can also help the better understanding. Since it is much harder to remember individual rules than one integrated conceptual structure, we can digest a notion, principle or conception only if becomes part of our representational network. The level of understanding is marked by the number, strength and stability of connections. Pictures, examples and experiences play a prominent part in forming an effective conceptual image (Vinner 1983). Vygotsky (1987) also emphasises the connection between the notions. Definition development goes together with the alteration of the structure of the system. Most of the subjects are characteristically



Adott az ABCDEF hatszög második képe és az A, B, C csúcsok első képe is. Határozd meg a D, E, F csúcsok első képét úgy, hogy benne legyenek az ABC síkban.

- Keresd meg a B"X" átló metszeteit az F"-n átmenő rendezővel!

- Ez lesz F'. A többi pontot hasonlóan szerkesztjük

Fig. 3.12 Interactive worksheet with construction tools and help (Nagyné Kondor 2008)

built on each other, since everything we learn is in connection with something that we already learnt before. Studies call our attention to the need to reveal the relationship between concepts, delineating it on a systemograph and structuring material based on this, since the concepts and the relationship between them make up the whole thing (Czeglédy 1988). If an arrow points from one corner of the graph to the other corner, it means that the second definition is built on the first one. The most important ability in working with Descriptive Geometry – apart from spatial ability – is the ability to perform operations on the basis of definitions. For the creation of definitions we need experience and examples. If students cannot connect the definitions with experience they cannot even apply them generally.

People dealing with Descriptive Geometry have probably had the experience that most students – without adequate spatial ability and conceptual structure – find this subject hard. They see some constructions not as logical steps of constructions; their solutions are characterized by memorized construction of lines and points. If they meet a new type of exercise that is a little bit different from the ones they practised you can easily see that their knowledge is superficial (Nagy-Kondor 2008a). Our program supports teaching Descriptive Geometry and helps the teacher to explain the theory and practice of Descriptive Geometry – Monge projection –, the reconstruction of the spatial objects in the mind, to develop the adequate conceptual structure, with the help of interactive feature to understand spatial relationships for the students with the help of Cinderella Dynamic Geometry Software (Nagy-Kondor 2006, 2008a, b; Nagyné Kondor 2008). Teacher can choose the set of initial objects and the objects that need to be constructed. After this the teacher can save the task with limited use of the construction tools. As we do not have to specify the way of the solution, only the set of desired objects, the program accepts several solution paths that may lead to the correct solution. For guidance on use of the worksheet, a construction aid can also be included. We attached a guide to the solution, and gave step by step solution (Fig. 3.12 – Created with Cinderella.). To help with the transparency of the construction, we usually set the added lines to grey colour, the x1,2 axis of Monge projection to blue colour and the outcome to red or black colour;

in practice we used a couple of other colours. The biggest difficulty in learning of geometrical construction process originates from the fact that students cannot grasp the sequence of the various steps and why each step is appropriate. To overcome this, we can apply the possibility of replay of construct steps. Worksheets exploit characteristics of Dynamic Geometry Systems and improve spatial ability.

As regards construction programs in the field of dynamic geometry, as well as traditional constructions and the preparation of static figures, we can shift the fundamentals of the construction at will. The figure being drawn thereby changes consistently, since the program views the figure as a dynamic whole. Moreover, these systems can store the construction steps and execute them after modification of the input data. So by means of movement it can be observed how figures are constructed upon each other, as well as the construction process itself (Kortenkamp 1999). If a constructed figure in the drag mode does not keep the shape that was expected, it means that the construction process must be wrong (Laborde 2001; Hölzl 1994). Looking at how students used dragging provided an insight into their cognitive processes (Arzarello et al. 2002). According to Fuys et al. (1988) dynamic manipulations help in the transition from the first to the second van Hiele level (van Hiele Level 1: Analysis; van Hiele Level 2: Abstraction) (van Hiele 1986). DGS is an appropriate material support for higher van Hiele levels.

According to Stylianides and Stylianides (2005) there are two criteria of validation for solutions of construction problems in dynamic geometry environments: Drag Test Criterion and Compatibility Criterion. Drag Test Criterion: Solution of a construction problem carried out in a Dynamic Geometry environment is a valid if and only if the final construction retains its geometrical properties under dragging. Compatibility Criterion: Solution of a construction problem carried out in a Dynamic Geometry environment is a valid if and only if the final construction retains its geometrical properties under dragging and its construction process does not violate the Dynamic Geometry environment construction restrictions (Stylianides and Stylianides 2005).

Hölzl (2001) distinguishes two ways of using the mediating functions of the drag mode: a test mode and a search mode. Hölzl (2001) conclude that “The analyses and supplementary observations from the overall research project indicate that such an advanced appreciation of the meaning of the drag mode is not a short term affair but develops in mutual dependence with the ability to grasp a geometric situation – a learning process that is characterised by different layers of conceptions” (Hölzl 2001, p. 83). Drag mode of Dynamic Geometry Systems accordingly reinforces in students the logical sequence of events. Dragging supports the production of conjectures and develop the spatial ability. The steps taken in a construction may be retraced and the construction can thus be analysed and logical mistakes and incorrect assumptions can be revealed.

The pictures of Fig. 3.13 show the use of the program’s dynamic features in Descriptive Geometry. On the left side moving the point P to the right side’s projection picture we can trace back the representation of the picture if our point is at the I., II., III. or IV. spatial quarter (Fig. 3.13 – Created with GeoGebra.).

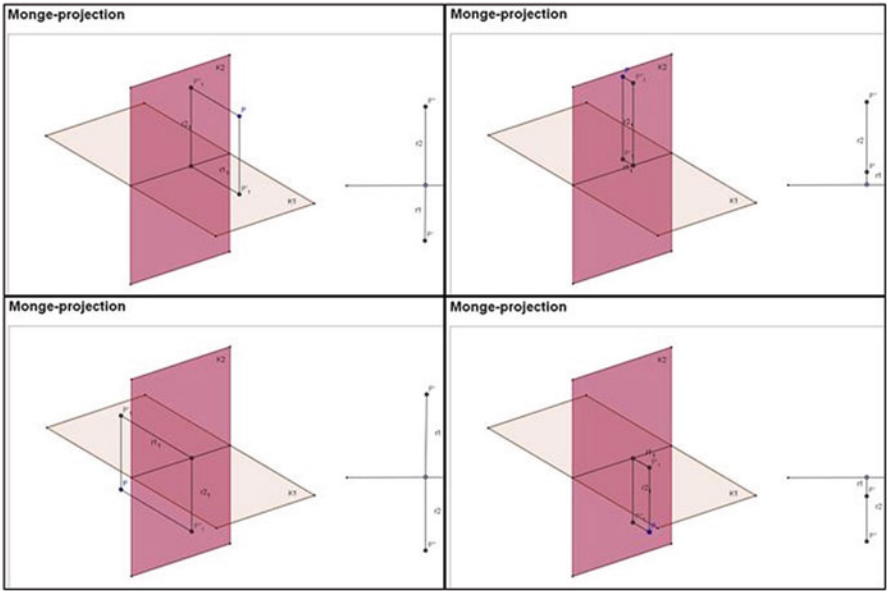


Fig. 3.13 Interactive worksheet 1: representation of a point in Monge projection (Nagy-Kondor 2010)

Figure 3.14 shows an interactive worksheet of Pyramid's plane section (Fig. 3.15 – Created with Cinderella.) This task itself takes its meaning from Dynamic Geometry System (Laborde 2001) (for example Black-Box tasks), with dynamic construction tools and features.

Our other examples with the possibility of replay of construct steps:

There are two planes, the first with the ABC triangle, the second with the 123 triangle, from which we cut out the 456 triangle. Construct the intersection of the two planes. To state the visibility you should consider the holes (Fig. 3.15 – Created with Cinderella.)

There are two solids. Construct the intersection of the solids (Fig. 3.16 – Created with Cinderella.)

It was observed that at the beginning the students did not use dragging very much (Arzarello et al. 2002; Nagy-Kondor 2006). To check their assumptions our students used rather the Undo and the eraser, since incorrect components can be cancelled with a single mouse click.

According to our observations (Nagy-Kondor 2006) the types of Undo used by students may be the following:

- Undo was used after an experimental step: This type serves to check the students' assumptions, ideas. The computer provides more facilities to make experiments, since incorrect elements can be cancelled quickly and other lines cannot accidentally be erased, as is the case with design on paper. However, this does not mean that the task be solved without any prior knowledge just by experimentation.

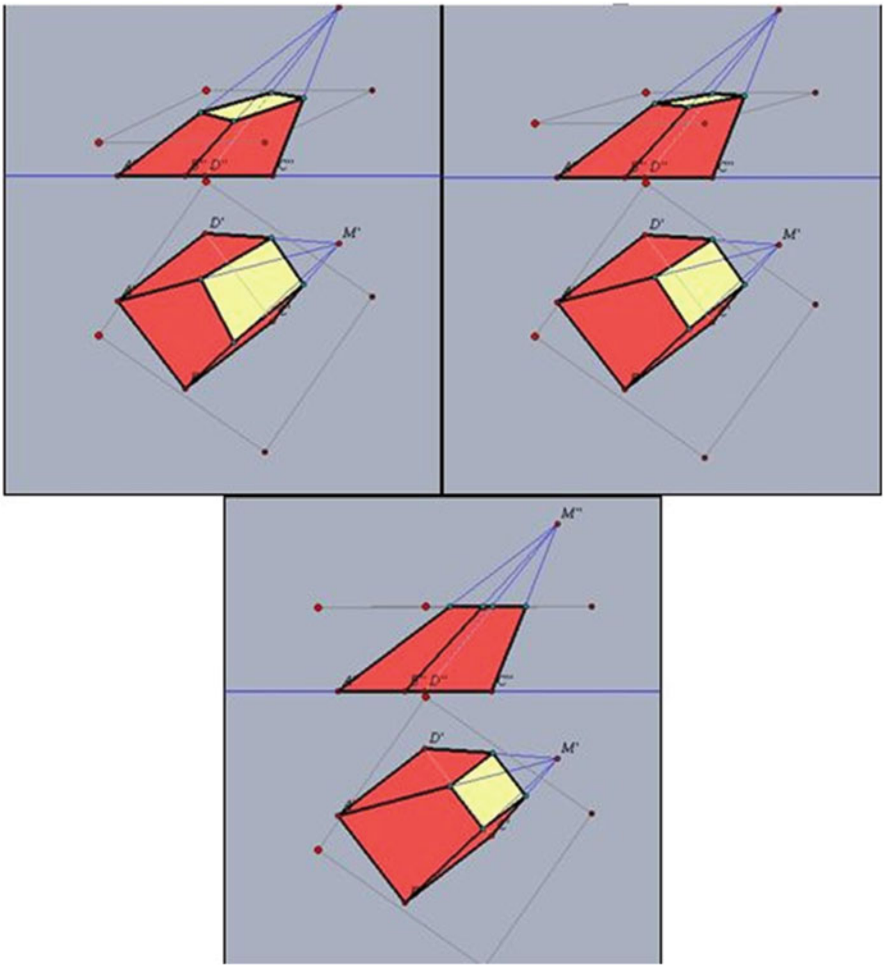


Fig. 3.14 Interactive worksheet 2: pyramid's plane section (Nagy-Kondor 2010)

- Undo was used after a logical mistake: Students would make the same mistake on paper as well.
- Undo was used after improper use of the software: In this case the mistake would not be made with paper and pencil.

We can draw a conclusion from our results that Dynamic Geometry Systems are useful aid in improving students' approach to geometry and spatial ability. Interactive worksheets can be used to advantage for teaching Descriptive Geometry in parallel with traditional construction. Students can check the validity of their solutions to problems of constriction by using the drag test criterion. We can state according to the results that the usage of the interactive worksheets increased the efficiency of the education, helps in creating the correct concept system. In the computer group it

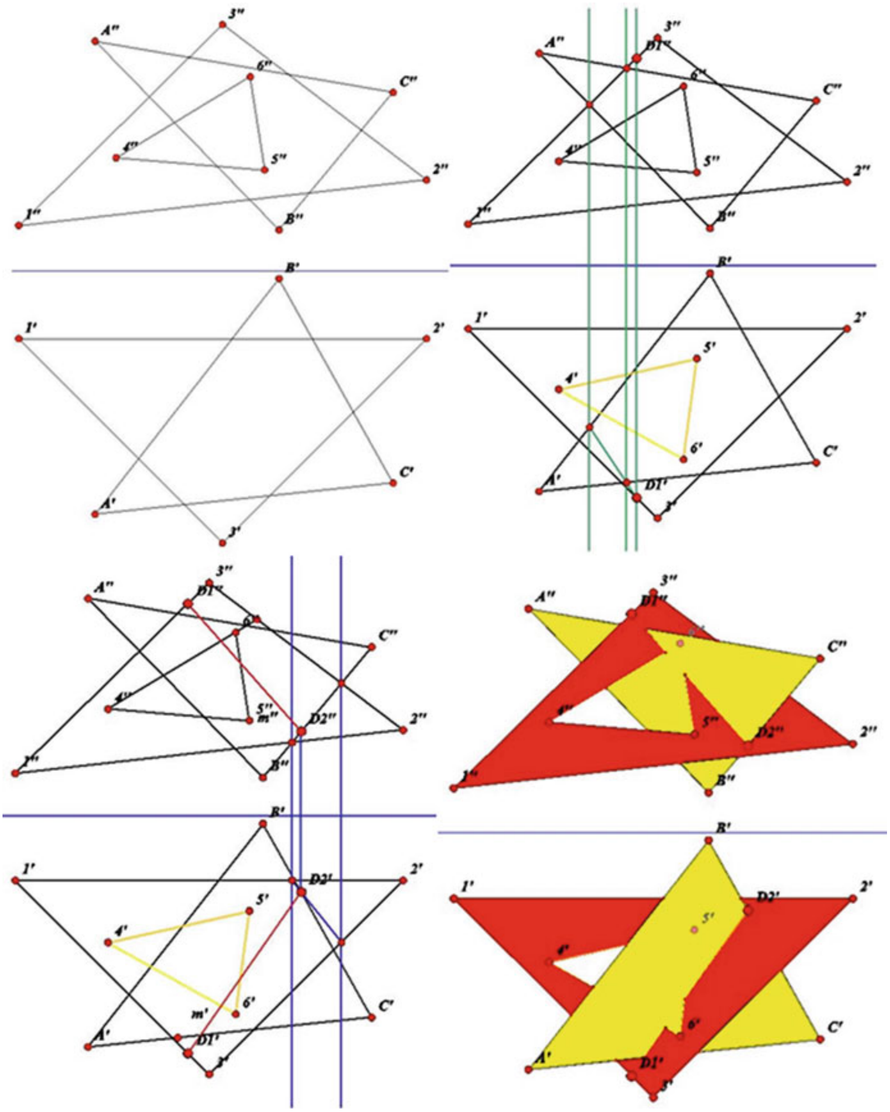


Fig. 3.15 Intersection of planes (Nagy-Kondor 2010)

was more typical that the students helped each other, corrected their mistakes. Experimentation was more typical for them as well, as the faulty elements could be hidden without any sign with a mouse click. The members of the paper-and-pencil group waited for the teacher's help, instruction when they stuck in their work. So the computer inspired the students for separateness (Nagy-Kondor 2008b).

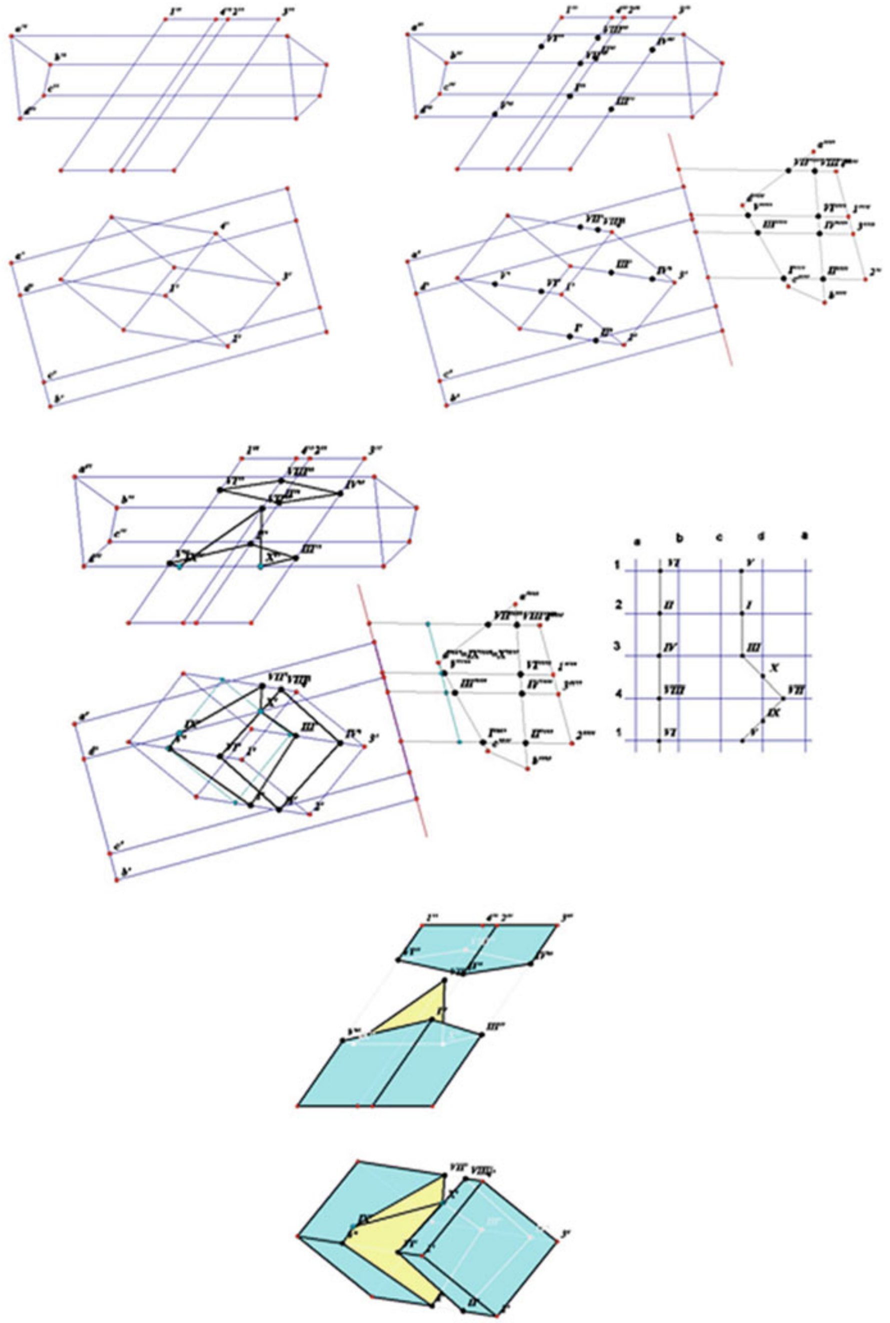


Fig. 3.16 Intersection of solids

It would be very useful for the university courses some review-systematization classes should be devoted for the summary of spatial ability, spatial geometry and solving spatial geometrical tasks. The effectiveness of teaching spatial geometry can be influenced to a great extent by using several different models, more technical drawings, manipulation activities with spatial models, especially dynamic, in the demonstration of relations between spatial models and operations with them. The three-dimensional models can be a great help in the teaching and learning of geometry (Origami, Kubus, etc.). It is much easier to imagine and represent different views of a solid when we can see the formal characteristics. The proper use and frequent study of spatial visual aids can result in such an inner spatial vision that makes the individual imagination of the spatial relations possible.

3.4 Conclusion

Spatial ability of students in several disciplines is of greatest importance in terms of their professional achievement. There are correlations between various measures of spatial skills and performance in particular STEM disciplines. Spatial ability for engineering students is very important, which decides of the future career. Yet the results of surveys verify that many students have problems with imagining a spatial figure, mental cutting and therefore to solve the spatial geometry exercises. There are not sufficient opportunities for high school students to learn geometry (Budai 2013). Therefore it would be very useful in the high schools and in the university training as well, if we devote more time for spatial ability, for summarizing the spatial geometry knowledge, for solving spatial geometry tasks.

How we can help students to develop their spatial ability, particularly in object rotations and views? Development of spatial ability by the aid of Information and Communication Technologies had great attention in the reviewed literature, especially with Dynamic Geometry Systems, interactive animation and virtual solids are promising tools for training spatial abilities. Development of the spatial ability is a very important task because we have to understand and develop the geometry knowledge of the students in the unity of the theoretical knowledge and the spatial abilities. Every skill, like the spatial ability as well can be developed at the right age with the suitable teaching strategy. It would be useful to start the teaching of spatial geometry with spending more time with the models of spatial solids, and should be devoted for the summary of spatial ability, spatial geometry and solving spatial geometrical tasks. The effectiveness of teaching spatial geometry can be influenced to a great extent by using several different models, manipulation activities with spatial models, especially dynamic, in the demonstration of relations between spatial models and operations with them. Let's provide many types of learning tools to the students. There are several types of students, thus our learning tools must be diversified as well.

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Chapter 4
Measuring Spatial Visualization: Test Development Study

Nazan Sezen Yüksel

4.1 Introduction

The innovations brought about by the present era provide various opportunities in every area including education. One of these innovations is to develop the abstract thinking skills and the creativity of students. When analyzed in this concept, the increase in the importance of spatial abilities concept and the increase in the studies on this ability has been inevitable. The importance of spatial ability, applied in many activities of daily life by individuals, is indisputable in scientific areas, especially in the field of mathematics.

The studies on spatial ability are based on different starting points. This situation has led to many different definitions and classifications about spatial ability. Labeling spatial ability by using different combinations of words like “visual”, “spatial”, “ability”, “skill”, “orientation” and “thinking” by many researchers and theoreticians on fields such as cognitive psychology, painting, science, mathematics and engineering is the most clear indicator of this (Miller and Bertoline 1991; cited in Mohler 2006).

Tartre (1990) identified spatial ability as a concept that contains spatial abilities like comprehension, manipulation, organization or interpretation of visual relations. Lohman (1993) mentioned different ability types that were identified by different viewpoints and determined spatial ability as retention, callback and transformation of visual pictures which are well-structured. Mayer and Sims (1994) have determined the spatial ability as envisioning of an object after situation changed, bent or rotated two or three dimensions of objects. Olkun (2003) identified spatial ability as a concept that contains skills about using geometric form and space usage. Towle et al. (2005) identified spatial ability as an ability to mentally represent the three

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dimension forms of given two dimension objects. Velez et al. (2005) has determined the spatial ability as transformation, retention and arrangement the visual knowledge within spatial context.

According to Sternberg (1990) the spatial ability that an individual has is measured by an individual's ability to visualization figures, rotation of objects and determining the missing pieces of a puzzle. Furthermore, Linn and Petersen (1985) have associated this ability with the presentation, transformation, generalization and memorization of the symbolic knowledge which is unconnected with language.

In line with much identification about spatial ability, there are also many classifications about this ability.

It can be said that, the basic research for the studies about determination of the components of spatial ability belongs to Thurstone (1938, cited in Bishop 1980). Thurstone, examines the basic mental abilities in his study where he has determined the mental process ability about spatial or visual objects as a "space" factor. Zimmerman (1953, cited in Bishop 1980) on the other hand, has reanalyzed Thurstone's data and revealed two spatial factors. The first of these factors is similar to Thurstone's space factor and has been examined as the mental manipulations of the objects or object relations. Zimmerman has called this factor as "spatial relations". The second factor is named as "visualization". It is indicated that, the tests developed for visualization have a tendency to be slower and more difficult than tests which are developed for spatial abilities.

Guilford et al. (1952; cited in Pellegrino et al 1984) has applied 65 ability tests on 8000 aviation students and the data obtained have been evaluated by factor analysis. According to the results of this study, the spatial ability factors have been identified as having five factors as "Spatial relations, Visualization, Spatial Orientation, Spatial Scanning and Perceptual speed". The first two factors have been determined in literature as they applied. The spatial orientation factor is characterized as "emphatic involvement" which has been composed of spatial considerations of the individual given certain orientation. The Spatial Scanning Factor is interested with finding the correct route in a test like a labyrinth by using design instead of visual mapping. Ultimately, Perceptual Speed factor has been determined as the speed of the identification of the localization of the letter in the letter string.

Lohman (1979; cited in Pellegrino et al 1984) has reanalyzed the studies on factor analysis and concluded that spatial ability has two large sub-factors. These two sub-factors are spatial relations and spatial visualization factors. Lohman has asserted that both sub-factors can be evaluated by distinctive tests or problem types. Also it is indicated in this study that the difference between spatial relations and spatial visualization tasks can be shown by relations of different performance dimensions. One of these is speed-power dimension that the individual spatial relations problems should be solved more speedily than spatial visualization problems. The second dimension is to examine the stimulant and cognitive process complication. It is remarkable that the complexities of spatial relations problems have shown more differences amongst themselves although spatial visualization problems have included less complicated stimulants.

McGee (1979) has stated that, before 1930s studies about the demonstration of spatial factor characterization existence were going beyond showing the absence of spatial factor characterization. But after this year, the studies about factor works have proved and supported two different spatial abilities strongly which were determined as “visualization and orientation”. Based upon these studies, McGee has, determined the visualization ability as “overturn, doubling and the ability of mental manipulation of a stimulant object shown as pictorial”. Also a different classification of spatial ability has been given by Linn and Petersen (1985). According to their classification; the sub-categories of spatial ability are signified as: spatial perception, mental rotation and spatial visualization. Gorska et al. (1998) has approached spatial ability as comprising of five components. These components are “spatial perception, spatial visualization, mental rotation, spatial relations and spatial orientation”.

According to recent studies, Allen (2003, cited in Yılmaz 2009) has grouped the spatial ability under three functional families. The determining object (answered the “what is this?” question); finding the place of object (answered the “where is it?” question); and mobile orientation (answered the “Where am I?” question). Carroll (1993) has scanned the studies about factor analytic in the literature and in his study; he has distinguished the components of spatial ability as having five dimensions like: spatial visualization, spatial relations, closing speed, closing flexibility and perception speed.

Spatial visualization, which is included in these classifications, is defined as one of the most important sub-dimensions of spatial ability. Just like spatial ability, spatial visualization is mentioned in numerous aspects in the literature. More importantly, it is observed that spatial ability and the concept of spatial visualization are used interchangeably in some studies. McGee (1979) defines spatial visualization as a subset of spatial skills which includes “the ability of mental manipulation, rotation, bending or to translate the inverse image of an object shown in the stimulus”. Fennema and Tartre (1985) define spatial visualization as “spatial ability tasks which require complex multi-step manipulations of information shown as spatial”. Carroll (1993) denotes spatial visualization as comprehension, coding and the mental manipulation process of three-dimensional images. According to Carroll, spatial visualization tasks require a connection in the direction from two-dimensional to three-dimensional images and in the opposite direction. Lappan (1999), however, describes visualization as “the mental coupling of visual information.” Olkun and Altun (2003) describe spatial visualization as the ability to create a mental picture of new conditions resulting from moving of two-dimensional and three-dimensional objects and their components in space.

4.1.1 Tests on Spatial Visualization Ability in the Literature

Different definitions on spatial visualization ability have caused this ability to be measured by various types of tests. As an example, Yue (2006) used Purdue Spatial Visualization Test (PSVT) in his study. Purdue Spatial Visualization Test was originally developed by Guay in 1977. In this test, there are questions regarding to

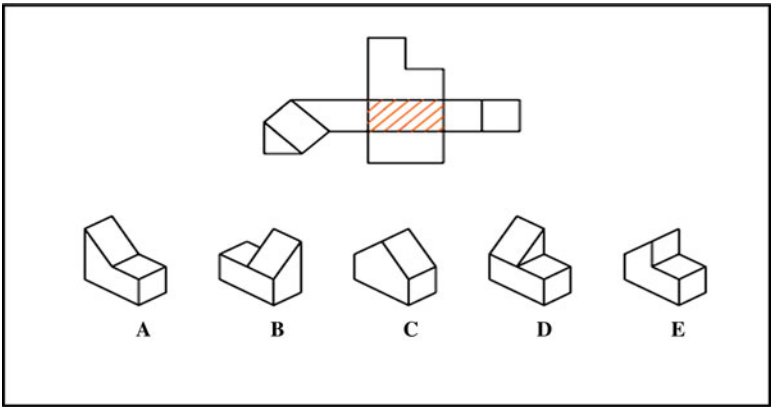

Fig. 4.1 A sample question for Purdue Spatial Visualization Test

three-dimensional surface models developed by folding two-dimensional flat-patterns (Fig. 4.1).

The test asks to determine the closed form of the object out of its opened form given above.

Linn and Peterson (1985) indicated in their studies that they used Embedded Figures and Paper Folding tests to determine the ability of spatial visualization. The Embedded Figures Test was developed by Witkin et al. (1977) to identify how the perception of an item by an individual is affected by the form it is in. The test consists of three sections. In the first section, the aim is to prepare the individual with seven figures for the initial stage of the test. This section is not taken into account in the assessment part as its aim is for preparation only. In the second and the third sections, there are 18 questions which require the detection of simple figures inside given complex figures (Fig. 4.2).

In the sample question about Embedded Figures test, the participants are required to find each figure above from the complex figures given beneath.

Paper Folding test was developed by French et al. (1963). The task of the students in this test is to determine the shape of the paper folded and punched on different points after it has been opened (Fig. 4.3).

In the above paper folding test, participants are asked to identify the unfolded form of the paper given as folded.

A different version of Paper Folding Test was developed by Kyllonen et al. (1984). In this test, the participants are asked to discover the opened final shape of a piece of square paper folded one or more times and punched on the folded parts (Fig. 4.4).

In this different version of paper folding test, participants are required to answer questions similar to the ones above and also to identify the opened form of a piece of paper folded once or more times and punched on the marked points.

Another spatial visualization test in the literature is "Dailey Professional Test (1965)" (Eliot and Smith 1983). In this test, the open and closed forms of figures are

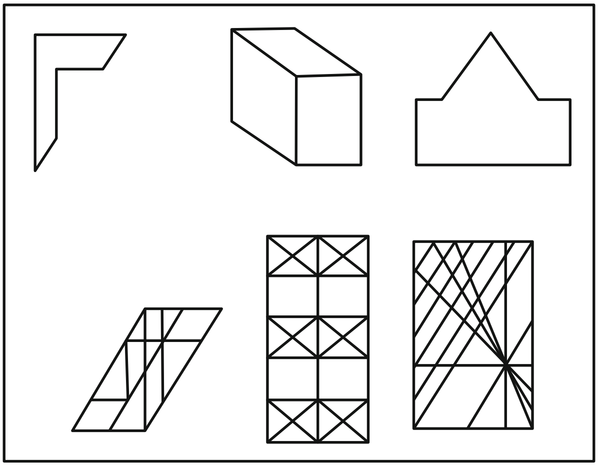

Fig. 4.2 A sample question for Embedded Figures Test

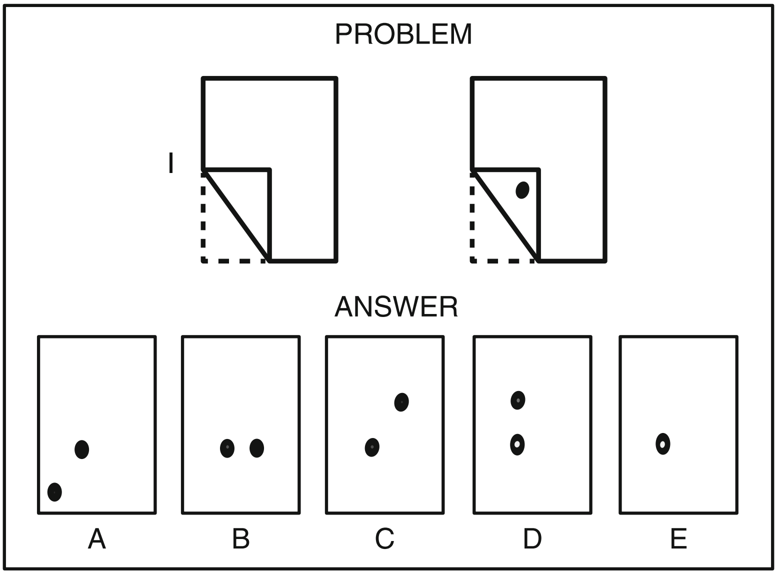

Fig. 4.3 A sample question for Paper Folding Test (French et al. 1963)

given and the participants are asked to match the forms of identical figures looking at their opened and closed forms. In Monash Spatial Visualization Test (1977), however, there are questions about cube formation and comparisons of various lengths (cited in Eliot and Smith 1983) (Figs. 4.5 and 4.6).

The question gives a diagonal of the object and asks participants to identify how many cubes having the same diagonal can be created.

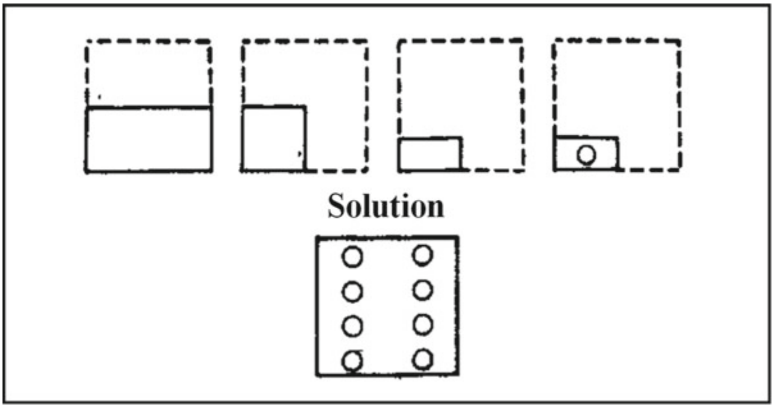

Fig. 4.4 A sample question for Paper Folding Test (Kyllonen et al. 1984)

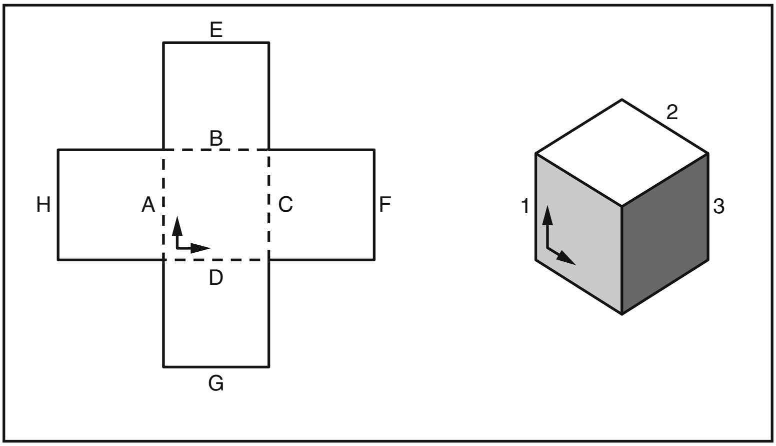

Fig. 4.5 A sample question for Dailey Professional Test

The last example for spatial visualization tests is the test of “Middle Grades Mathematics Project: Spatial Visualization”. This test was prepared for the project called “Middle Grades Mathematics Project” conducted in U.S.A. for middle grades at primary education and then developed by Winter et al. (1989). The test consists of 15 questions. There are five choices for each question. In addition to the isometric appearance of structures composed of unit cubes, test questions include questions regarding these structures’ view from right, left, front and back. Moreover, in this test, there are questions about MAT plans which constitute the special code of the view of the structures from above (Fig. 4.7).

In the question, given the front right view of a figure participants are asked to identify the rear view of the same figure.

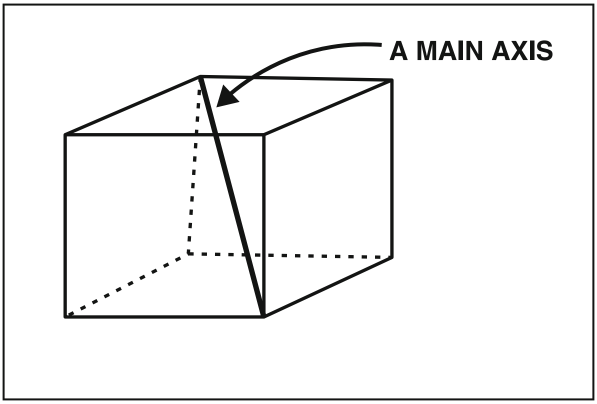

Fig. 4.6 A sample question for Monash Spatial Visualization Test

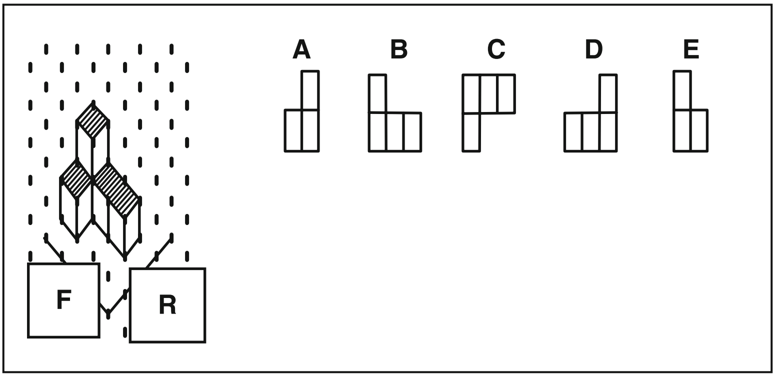

Fig. 4.7 A sample question for Middle Grades Mathematics Project: Spatial Visualization Test

4.1.2 Activities Performed to Develop the Spatial Visualization Ability

Christou et al. (2007) defend the necessity of dynamic and interactive computer applications holding the features of appropriate 3D objects to develop 2D and 3D spatial visualization and reasoning abilities. For this aim, they emphasize that the visual conception of students can be enhanced with the help of dynamic geometry software (Cubix Editor) they have created.

In their studies, Rafi et al. (2008) conducted research on the effects of instructional method on spatial visualization ability. Within the scope of the study, students were divided into three groups consisting of two experiment groups and one control group. While the first experiment group was trained with interactive-based and the second experiment group in an atmosphere developed by animation-based methods, the control group was trained with traditional methods. At the end of the study, they concluded that the most progress was achieved through interactive-based methods; average progress was made in an animation-based atmosphere, whereas no progress was made with traditional methods.

In addition, in another study, Rafi et al. (2006) have shown that spatial visualization ability can be developed by computer-aided engineering drawing. For the development of this ability, Interference Engineering Drawing (EDwgT) education and two types' conventional techniques have been applied. In one of these conventional techniques, written materials have been used by utilizing digital videos. In the second technique, written materials have been used without any enhancing effect. According to the findings obtained; the spatial visualization ability of students which have been applied EDwgT education, has not shown meaningful increase.

In his semi-experimental study with graphic engineering students, Gillespie (1995, cited in Idris 2005) investigated the effects of education with three-dimensional models on the development of three-dimensional visualization abilities. During a 10-week training period, students were trained with three-dimensional modelling training prepared, within the scope of the study. According to the results of the analysis obtained from tests which were applied during the assessment process, a significant increase was observed in the visualization abilities of experiment group compared to other groups.

Robinson (1994) in his study carried out with seventh class students, has examined the relationship between spatial visualization ability, mathematical ability and problem solving strategies, by Geometer's Sketchpad software. Cube Comparison, Card Rotation and Paper Folding tests have been used as measurement tools in this study. The group, which used Sketchpad software, was specified as the experiment group whereas the other group not using this software was specified as the control group. Both groups have been trained by geometry lecture. According to the results; the spatial visualization and active participation to educational activities performances of the students that have been educated by technological support have increased.

Cohen and Hegarty (2008) have designed two different experiments in their study with the aim of development of the spatial visualization abilities of the students. They have used animations that show the surface of the sections by cutting a section of the regular three dimensional shapes like pyramids, prisms, cylinders, cubes and cones that drawn by 3d Max. After both experiments it has been concluded that the spatial visualization ability can be developed by education and, in this education, interactive computer visualizations are quite useful.

Takahashi (2011) has computerized "Purdue Spatial Visualization Test: Rotations" test by using 3d Max software. With this software, Takahashi has defended that he can increase the depth of visualization for students better and he observed at the end of the study that the levels of spatial visualization ability of the students with low ability have shown increases after the application of the three dimension environment.

4.1.3 The Importance of Spatial Visualization Ability on Mathematical Area

Another area where spatial ability is often applied is mathematics. It is due to the fact that the identifications and functions of both spatial ability and its sub-dimensions are found to play a significant role in mathematics as well. In support of this claim, Halpern (2000), has emphasized that mathematics requires spatial ability because of both its subjects (geometry, topology, trigonometry, etc.) and its nature. Also Krutetskii (1976; cited in Idris 2005) has indicated that spatial visualization was a kind of mathematical ability and he has also professed that this ability was not an inborn attribution like mathematics, but rather it could be restructured by improvement. The common results received from different studies show that the deficiency of basic visualization skills of some students causes them to perform below expectations (Clements 1998; Del Grande 1987).

Sundenberg, in 1994, conducted studies in a summer school mathematics project with a 34 student sample comprising of six to eighth class students, with the intention of determining the effect of spatial education and geometry education on spatial performance and mathematics success. In this study, students have been separated into four groups randomly. Concrete materials were given to Spatial Group 1 and 2 to develop their spatial visualization skills; Geometry Group 1 and 2 were educated traditionally by using 8th class math book. All students had training in geometric concepts education for 25 h. Both before and after training, a mathematics achievement test and Secondary Education Mathematics Project Spatial Visualization test were applied to all students. According to the findings, the spatial visualization abilities of Spatial Groups increased more than Geometry Groups. However, neither of these groups showed an increment on mathematics success test results (Idris 2005).

Idris (2005) has examined the importance of cognitive variables of spatial visualization ability on geometry success and the effect of chosen educational activities on spatial visualization and geometry success in his study. In educational activities, shapes have been given for the questions in the Spatial Visualization Test (SVT) to the students. According to obtained results of the study, a significant correlation as .56 level between spatial visualization ability and geometry success was found. Also, it has been found that the educational activities have positive effect on the spatial visualization ability.

Presmeg (2006) has indicated that mathematics is a subject that has diagrams, tables, spatial arrangements of signifiers such as symbols, and other inscriptions. Hence, spatial visualization is one of the important basic abilities in learning and studying mathematics.

Van Garderen (2006) has expressed that there is an important difference among those who use visualization skills to solve math problems, those who use “schematic imagery” and those who use “visual imagery”. Schematic problem solvers use spatial relation in their visualizations and diagrams, while those who only use visual identifications do not. This research results show to confirm the notion that there exists such a distinction between schematic imagery and visual imagery.

4.1.4 The Importance of Spatial Visualization Ability for Other Disciplines

The spatial visualization ability's relation with many branches is mentioned as a research topic for the studies in different disciplines. These studies have a wide range like painting, education, science and engineering fields.

Many studies, emphasize the importance of spatial visualization ability by indicating that this ability is a presupposition for science subjects. Furthermore, a significant relationship between success on science branch and spatial ability has been shown in these studies (Aris et al. 2010).

Kozhevnikov et al. (2007) have examined the relationship between spatial visualization and solving physics problems in their study. For this purpose three works on kinematic problems have been prepared by researchers and their relationships have been examined. In the first work, the estimation of the two dimension movies of an object was explored, in the second work the transition from a reference (an observer) to another one, and in the third work the skill of explaining of kinematic graphics and spatial visualization abilities have been analyzed. According to the findings obtained from research, it is concluded that; spatial visualization has a meaningful correlation with kinematic problem solving in Work 1 and Work 2. Work 3 also verified this relationship as strong and meaningful.

Macnab ve Johnstone (2010) has expressed that spatial tests do not dependent on biology knowledge but these tests have indicated the necessary abilities for the biology. They have specified these abilities as follows:

- The visualization ability of two dimension sections taken from three dimension structures
- The visualization ability of three dimension structures composed from given two dimension section
- The ability to distinguish the change in orientation of a structure

These studies have found that there is a relationship between spatial visualization in genetic lectures and the success for the learning of genetic concepts like as dihybrid crosses, meiosis, Hardy-Weinberg theorem, peptide bonds occurrence and nitrogen base/amino acid relation (Costello 1985, cited in Lennon 2000).

Wu and Shah (2004) have examined the structural relational research about chemistry education and spatial visualization their study. For this purpose, they have researched the studies published on different databases in 1966–1987 and they have pointed out the positive correlation between spatial visualization ability and success on chemistry education.

4.1.5 The Analysis of Spatial Visualization Ability in Relation to Gender

It has been revealed through a number of studies that spatial visualization ability differs significantly in relation to gender and it is in favor of males. For instance, the results of research conducted by Rafi et al. (2008), express that the spatial visualization ability of men is higher than that of women. However, Eisenberg and McGinty (1977), according to their study for university students registered on two different mathematics programs (calculus and occupation statistics), female students have higher spatial visualization performances than male students.

In a study analyzing the mathematical performance and different cognitive abilities in relation to gender, Maccoby and Jacklin (1974) came to a conclusion that spatial visualization significantly differs in favor of male students. In addition, the identification of the fact that this difference is not present at primary education, but arises during the adolescence period, is another important result of the study.

McGee (1979) mainly presents four reasons for the difference in spatial visualization ability according to gender. These reasons are environmental, genetic, hormonal and neurological factors. The factors mentioned related to hormones result from estrogen and androgen hormones. In the scope of McGee's study, it was discovered that high levels of androgen hormone signifies low level of spatial ability. Another factor expressed under the heading of neurological factors is related to the development of brain hemispheres.

Deno (1995) has indicated that there is a direct relationship between spatial visualization ability of engineering students and spatial experiments which are not concerned with academic subjects. Additionally, Deno has emphasized that spatial experiments differ greatly according to gender. As a proof of this situation he has shown that, during the bloc setting of toy types, male students use visualization but female students consult touching activities mostly.

As opposed to the studies in the literature which support that spatial visualization differs significantly in relation to gender, there are also some studies that claim the opposite. In the study which investigated the solution strategies and gender variables in spatial visualization tasks, Burin et al. (2000) proposed that there is no significant difference in spatial visualization tasks in relation to gender. Similar results were also found in Linn and Peterson's (1985) studies. According to the aforementioned study, the difference of spatial visualization ability among genders is very little or non-existent.

4.1.6 The Aim of the Study

The aim of this study is to develop a new spatial visualization test involving mathematical context different from tests in the literature. Questions in different categories were prepared on the basis of other spatial visualization tests analyzed with this purpose. By requiring the establishment of a relationship between three-dimensional figures with curves and by rotating these curves around axes in the categories created according to the purpose of this study, a different approach is taken towards spatial visualization.

4.2 Methodology

In this part of the study, there is information on the assessment tool and the development stage. This study is a test development study. Downing (2006) has organized 12 steps for developing an effective and efficient test as follows;

- Overall plan: construct, desired test interpretations, test format, clear purpose…
- Content definition: sampling plan for domain, various methods related to purpose of assessment,
- Test specifications: operational definitions of content, framework for validity evidence related to systematic…
- Item development: development of effective stimuli, formats …
- Test design and assembly: designing and creating test forms …
- Test production: publishing activities …
- Test administration: validity issues concerned with standardization …
- Scoring test responses: validity issues, quality control …
- Passing scores: establishing defensible passing scores …
- Reporting test results: validity issues; accuracy …
- Item banking: security issues, usefulness …
- Test technical report: systematic, detailed documentation …

In consideration of given items, according to expediency level of purpose, the following processes have been made for the composition of each item's content.

4.2.1 Preparing the Test Items

The "Spatial Visualization Test" has been designed as six parts to be used in this study by researcher. The expectation from a student who performs acceptably in this test are as follows:

- Can determine the three-dimension form of geometric shapes after they are rotated around an axis of two-dimension geometric shapes.
- Can determine the three-dimension shapes resulting from which two-dimension shapes after rotating around any axis.
- Can identify the close state of a three-dimension object from a given open state.
- Can identify the open state of three-dimension object from a given close state.

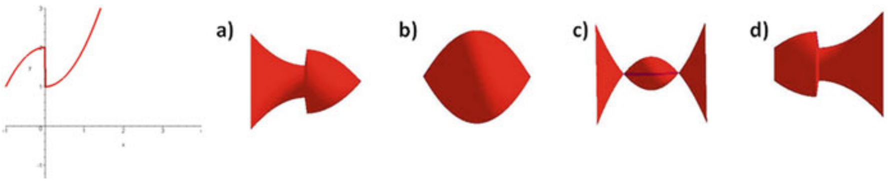

Fig. 4.8 A sample question for the first category

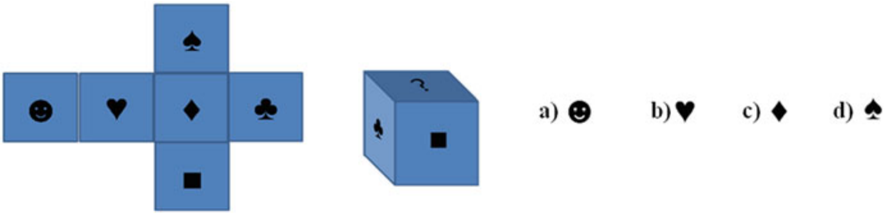

Fig. 4.9 A sample question for the second category

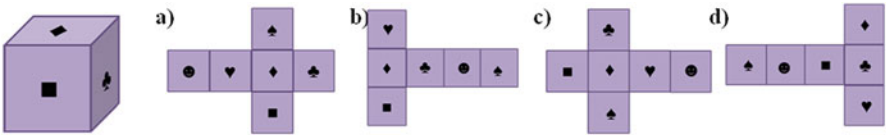

Fig. 4.10 A sample question for the third category

At the beginning of the test development stage, questions in 6 categories were prepared trough an analysis of spatial visualization tests in the literature. In the first of these categories, students are asked to determine the possible three-dimensional shape which will be formed by the rotation of a planar curve around the x- or y- axis (Fig. 4.8).

The question which is given as a sample above requires the participant to choose the correct image of a three-dimensional object of the curve which is created after rotation around the x-axis.

In the second category, there is an open cube with shapes on all sides and the students are asked to identify the possible shape on any blank side of the cube after being closed (Fig. 4.9).

Contrary to the second category, in the third category students are asked to identify which option cannot be represent the opened form of the cube (Fig. 4.10).

The questions in the fourth category are designed to identify the closed form of non-uniform shapes when folded. The questions here were employed from the test called “Differential Aptitude Tests (DAT)” developed by Bennett et al. (1974) (Fig. 4.11).

Finally, as opposed to the first category, in the questions of the fifth and sixth categories, the students are presented with a three-dimensional shape and expected to identify from which planar curve rotating around the x- or y-axis respectively the three-dimensional shape has been formed (Fig. 4.12).

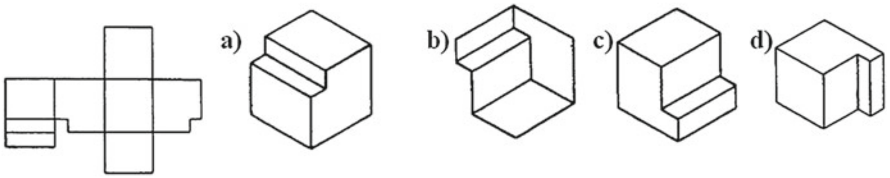

Fig. 4.11 A sample question for the fourth category

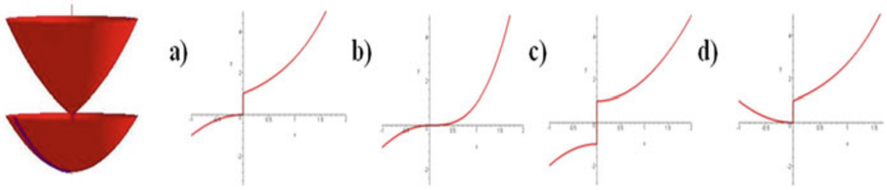

Fig. 4.12 A sample question for the fifth and sixth categories

4.2.2 The Pilot Application of Prepared Test

The test was piloted with 236 students studying on mathematics and mathematics education programs at two state universities in Türkiye. In the literature it has been emphasized that the pilot application group must be comprised of at least a hundred people and it would be been more realist if the group is comprised of around 200 people (Baykul 2000).

There is no demographic information section in this test since the academic standing and class levels of students have not been considered. The factor that is emphasized most during pilot application process was "time limitation". In the literature on some studies about spatial ability and its components, it has been indicated that time limitation has played a significant role disabling the students to display their real performance (Goldstein et al. 1990; Cherney and Neff 2004). Due to these reasons, there was no time limitation to students during the process of pilot application of this test.

4.2.3 Analysis of Obtained Data

Following the preparation of items in the test, some changes were made in both the forms and question statements of these items in accordance with the opinions of experts. The pilot application of the test has been applied in this form, and using the data obtained from this pilot application, item analysis and then validity and reliability analysis have been undertaken.

The item analysis of the items in the test from the pilot application has been performed with Iteman 3.5 statistics software. From the item analysis of the test, item difficulty coefficient and item discrimination index for each item has been obtained. As a criterion to comment on the item discrimination index, the values designated by Ebel (1965; cited in Crocker and Algina 1986) have been used. According to this, the item discrimination index is;

- Items on 0.19 and below can absolutely not be put in the test.
- Items between 0.20 and 0.29 are liminal items and if necessary, they can put in the test after rectification.
- Items between 0.30 and 0.39 can be put in the test without rectification or with minimal rectification.
- Items on 0.40 or greater are well processor items and can be put in the test exactly the same.

With regard to the Item Difficulty Factor, the items mostly with middle difficulty (approximately 0.50) are preferred in order to be suitable for the purpose of test. However, whether the item difficulty indexes have normal discrimination or not, has been determined in consideration of the suggestions in the literature (Baykul 2000).

For the test reliability study, in consideration of data obtained from pilot application, Cronbach Alfa has been used based on internal consistency method. Khaing et al. (2012) have not chosen test – retest reliability method due to the risk of participants remembering the items in the second application since spatial ability tests are generally comprised of shapes. Due to the same concern, in this study it has been deemed sufficient to calculate the internal consistency by Cronbach Alpha, which is based on one application. To determine the reliability of the developed test, reliability analysis using SPSS 17.0 software has been conducted.

A criterion related validity method has been used for the test validity in this study. In this study, another criterion is a test that admitted measurement as spatial visualization ability in the literature. Both the application of the test in literature and the test developed for this test are applied to the same group and the correlation of the points obtained from the two tests have been determined. Another process used as a proof of validity for the test is to determine if some results of spatial visualization in the literature are also obtained from the developed test or not. Therefore; the result determined has been that, in the literature the differentiation of spatial visualization ability on the basis of gender is meaningful. In addition, as the proof of the validity of the study, the last process is confirmatory factor analysis. The confirmatory factor analysis of the data obtained from applying the test has been performed with Lisrel 8.7 statistics software. For the interpretation of the findings obtained from confirmatory factor analysis, fit indices criteria determined by literature have been considered. The criteria of fit indices and cut points for acceptance as follows (Çokluk et al. 2010) (Table 4.1):

Table 4.1 Fit indices criteria for confirmatory factor analysis

Fit index	Criteria	Cut points for recognition
X^2/sd	p > 0.05	≤2 perfect fit
		≤2.5 perfect fit
		≤5 moderately fit
GFI/AGFI	0 (no fit)	≥0.90 well fit
	1 (perfect fit)	≥0.95 perfect fit
RMSEA	0 (perfect fit)	≤0.05 perfect fit
	1 (no fit)	≤0.06 well fit
		≤0.07 well fit
		≤0.08 well fit
		≤0.10 weak fit
RMR/SRMR	0 (perfect fit)	≤0.05 perfect fit
	1 (no fit)	≤0.08 well fit
		≤0.10 moderately fit
CFI	0 (no fit)	≥0.90 well fit
	1 (perfect fit)	≥0.95 perfect fit
NFI/NNFI	0 (no fit)	≥0.90 well fit
	1 (perfect fit)	≥0.95 perfect fit

4.3 Findings

The findings related to the item, validity and reliability analyses of Spatial Visualization Test developed within the scope of the research is as follows:

4.3.1 The Findings of the Item Analysis on Spatial Visualization Test

According to the item analysis results, the difficulty level among items is identified as 0.27, minimum and 0.66, maximum. The values of other items range from 0.34 to 0.72. With this information, the difficulty level of the test can be accepted to be average.

Item difficulty factors for 29 items and One-Sample Kolmogorov-Smirnov test have been realized based on whether item difficulty indexes have shown normal distribution or not. The results of this analysis are as follows:

Table 4.2 One-sample Kolmogorov-Smirnov test for item difficulty

		İtem difficulty coefficients
N		29
Normal parameters	Mean	.4324
	Std. deviation	.10534
Most extreme differences	Absolute	.080
	Positive	.064
	Negative	–.080
Kolmogorov-Smirnov Z		.429
Sig (2-tailed)		.993

Table 4.3 The results of the item analysis

Number of items	29
Number of examinees	236
Mean	19.86
Standard deviation	5.697
Skewness	–0.755
Kurtosis	0.383
Mean item difficulty	0.492
Mean item discrimination	0.573

As is seen in Table 4.2; the relevance value is found as .993 for Kolmogorov-Smirnov test.

In terms of discrimination level of items, the coefficient of the lowest item is 0.24, while the highest is 0.64. The values related to other items range from 0.31 to 0.61. The results of this analysis are presented in Table 4.3.

4.3.2 *The Findings Related to the Reliability of Spatial Visualization Test*

The items developed for the test were graded in accordance with answers as 1-0 dichotomously. During the reliability test of data collection tools, the internal consistency of coefficient of Cronbach α was taken into consideration. Although the obligation of using KR-20 technique in dichotomous grading is emphasized in the literature, it is known that when all items are graded as 1-0; KR-20 and the coefficient of Cronbach α have the same results (Cronbach 1951). Cronbach α coefficients belonging to the spatial visualization test developed within the scope of the study was found as .84.

4.3.3 The Findings Related to the Validity of Spatial Visualization Test

In this part, there are studies conducted to prove the validity of spatial visualization test. To find evidence for the construct validity of the study, the correlation between the spatial visualization test and another test accepted to evaluate the same ability was searched. In addition, it was checked whether or not the features identified in research were also obtained in the test developed for the study.

To find evidence for the construct validity of spatial visualization test (SVT), "Spatial Visualization Test (SVT*)" developed by Winter et al. (1989) was applied to 128 students in the research group. The data obtained from the application of these two tests to the same work group have been used in a correlation analysis using SPSS 17.0 software. The findings according to result of analysis are as follows (Table 4.4);

According to the results of the analysis, a significant positive correlation at the level of .66 was found between the Spatial Visualization Test developed for the study and the Spatial Visualization Test developed by Winter et al. (1989).

In the other part of the reliability test, the focus was on the question of whether the results from the tests applied in the literature were valid for the test developed for this study or not.

In their studies, Vandenberg and Kuse (1978) and Hamilton (1995, cited in Alias et al. 2002) expressed that men's spatial visualization abilities are at higher level compared to women's. Ben-Chaim et al. (1989), in their studies, concluded that

Table 4.4 The correlation analysis between the SVT* and SVT

		SVT*	SVT
SVT*	Pearson correlation	1	.667**
	Sig (2-tailed)		.000
	N	128	128
SVT	Pearson correlation	.667**	1
	Sig (2-tailed)	.000	
	N	128	128

**Correlation is significant at the 0.01 level (2- tailed)

Table 4.5 The analysis of the spatial visualization test in accordance with gender

	Levene's test for equality of variances	t-test for equality of means					
	F	Sig.	t	df	Sig (2-tailed)	Mean difference	Std. error difference
Equal variances assumed	2639	.106	–11.540	229	.000	–7.357	.638
Equal variances not assumed			–10.995	134.1	.000	–7.357	.60091

male students have better spatial visualization abilities than female students. Similar results can be seen in the studies of Baenninger and Newcombe (1995).

To identify whether there is a difference according to gender in the test developed for this test and find out for with which group the ability is better, if there is really a difference, independent sample t-test was applied. The results of the analysis obtained for both tests are as follows:

According to the results of the analysis in Table 4.5, it is seen that the spatial visualization test developed for the study shows significant difference depending on gender and more importantly this difference is in favor of male students.

4.3.4 The Findings Related to the Confirmatory Factor Analysis

The last step performed to prove validity is Confirmatory Factor Analysis. For the application of confirmatory factor analysis, one of the factoring techniques of Maximum Likelihood Factor Analysis is used. This technique, developed by Lawley in 1940s, estimates the values of the research population for the factor loads on the possibility of the highest calculated load values of the correlation matrix sample captured and observed from the research population. The Maximum Likelihood Factor increases the canonical correlation between factors and variances to the highest size (Tabachnick and Fidel; cited in Çokluk et al. 2010). An important advantage of this analysis is that it provides opportunities for statistical evaluations related to how it is possible to make better factor analysis to reorder the relationships among indicators in the data set (Çokluk et al. 2010). However, Maximum Likelihood Factor Analysis requires the assumption of a multi-variable normal distribution for variables and if the data set does not meet this assumption, it may lead to a distorted and non-valid result (Brown 2006; cited in Çokluk et al. 2010).

Based on this information, whether or not the data obtained from the application of this test met the assumption of normality was analyzed before the confirmatory factor analysis which would be applied to the data collection tool in the study (Table 4.6).

As the obtained values of p is >0.05 when the results of One Sample Kolmogorov-Smirnov Analysis are studied, it is determined that the data obtained from this test verifies the assumption of normality.

The conformity indices obtained as a result of the verification factor analysis carried out after determining normality assumption are as follows (Table 4.7):

It has been considered appropriate that, according to modification suggestions which have been obtained from analysis results, the cause of significant contributing to χ^2; removing the 8. and 16. items from the test and, besides, connecting 6. and 7. items to each other. According to this fit indices in final position have been obtained as CFI = 0.97, RMR = 0.014, GFI = 0.90, NNFI = 0.96 and RMSEA = 0.032. The determination of the obtained fit indices have pointed that NNFI = 0.96, RMR = 0.014, CFI = 0.97 and RMSEA = 0.032 indices to perfect fit for this model,

Table 4.6 The analysis of spatial visualization test related to the assumption of normality

		t
N		235
Normal parameters	Mean	15.40
	Std. deviation	6.427
Most extreme differences	Absolute	.075
	Positive	.075
	Negative	–.047
Kolmogorov-Smirnov Z		1.154
Sig (2-tailed)		.139

Table 4.7 The confirmatory factor analysis for the spatial visualization test

	Goodness of fit statistics
Comparative Fit Index (CFI)	0.91
Root Mean Square Residual (RMR)	0.015
Goodness of Fit Index (GFI)	0.86
Non-Normed Fit Index (NNFI)	0.93
Root Mean Square Error of Approximation (RMSEA)	0.042

GFI = 0.90 to well fit (Hooper et al. 2008; Sümer, 2000; Jöreskog and Sörbom 1993, cited in Çokluk et al. 2010).

The path diagram after the application of confirmatory factor analysis is as follows (Fig. 4.13).

4.4 Results and Conclusions

Although there have been a large number of research studies on spatial ability and its components in which different definitions and different assessment tools have been developed, the common point these studies unite is the importance of this ability.

The spatial visualization ability is one of the most important components of spatial ability and has many areas of utilization in many disciplines. It also increases success of each discipline. But in literature research, the point which draws the most attention in these studies is the fact that although participating students have different features, they are assessed with the same test (Khaing et al. 2013; Mäntylä 2013). Therefore, the results obtained from studies being comparable with each other or making inferences from these studies seem possible. This situation has been seen as a cause for developing the spatial visualization tests, just as the subject to this study.

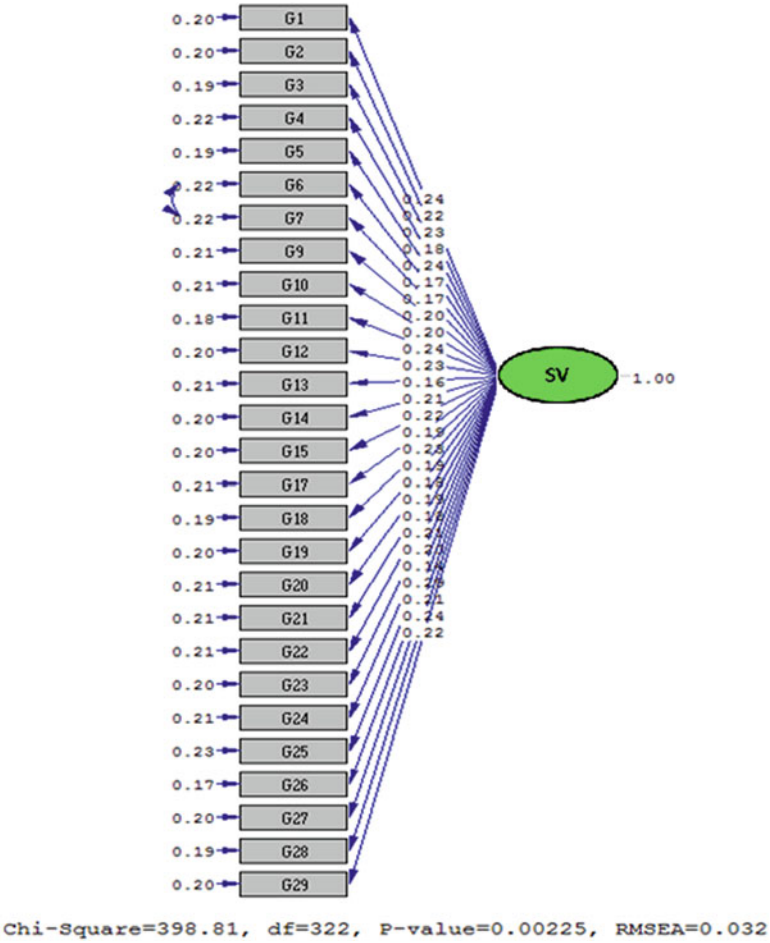

Fig. 4.13 The path diagram for the spatial visualization test

Considering this situation as the starting point of this study, the study aims to identify the spatial visualization abilities of students studying mathematics or mathematics education with field-specific questions as well as classical spatial visualization questions. Thereby, the test developed within the context of this study diverging from and the tests in literature, the undergraduate students have been determined as target group by the test that includes mathematical context.

In the first step of test developing, the spatial visualization tests in the literature and others of these tests, the tests for the other components of spatial ability like mental rotation, mental cutting and spatial orientation have been researched. The aims of researching the tests for other abilities is (1) to make a perception about what is the characteristic difference of this ability from the other ability types and (2) to prepare the items in the test to be developed according to this content. The target behaviors have been determined that will be measured by the developed spatial visualization test as a result of researching related literature.

According to this; the expectations from a student who capable of doing this test can determine the three-dimension form of geometric shapes after turned around axis of two-dimension geometric shapes, can determine the three-dimension shapes that become which of two-dimension shapes after turn around any axis, can identify the close state of three-dimension object which given open state and can identify the open state of three-dimension object which given close state.

In accordance with determined source behaviors, the spatial visualization test developed for this aim and consisting of 29 questions was introduced with a study applied to 236 undergraduate students studying mathematics and mathematics education at two different universities. As a result of the reliability analysis, the Cronbach alpha coefficient was found as .84. According to this, it can be said that the reliability of the test is at a high level (Salvucci et al. 1997).

For the purpose of supporting a proof for the validity of the test, the test was compared to another test (Winter et al. 1989) in the literature and is accepted to test the same ability by studies. A significant positive correlation level .66 was observed between the data obtained from the application of the two tests. Both tests also showed the same properties when gender factors were taken into consideration. With the help of the data, the validity and reliability of the test were tried to be proven.

In the other part of validity study of the test, it has been examined that if both tests have had the same properties with regards to the determined variable or not. At this stage, the variable to be examined has been approached as “gender”. In the literature many studies have shown that the spatial visualization ability has shown meaningful difference according to gender. Furthermore it is concluded that this difference is in men’s favor (Rafi et al. 2008, Maccoby and Jacklin 1974; Rafi and Samsudin 2007). As a result of the application of t-test statistical analysis of the data obtained from the test which was developed for this study context, it has been concluded that spatial visualization ability has shown meaningful difference and this difference is in men’s favor. These results show consistency with literature, it can be shown as a proof for test validity.

The fit indices obtained from the confirmatory factor analysis of spatial visualization test have been found in the first stage as CFI = 0.91, RMR = 0.015, GFI = 0.86, NNFI = 0.93 and RMSEA = 0.042. In accordance with the modification suggestion, after removal of two items from the test and connecting two items in the test with each other, the result has been found as CFI = 0.97, RMR = 0.014, GFI = 0.90, NNFI = 0.96 and RMSEA = 0.032. It can be said that fit indices generally indicate a perfect fit. The obtained fit indices have indicated perfect fit, and this is proof for validity and reliability process of the test is proven as having been conducted properly. After confirmatory factor analysis, the test has taken its final forms as a 27 items.

4.5 Suggestions

With the aim of identifying the spatial visualization abilities of students, the test mentioned in this research was developed with the addition of a mathematical context. It is predicted that the spatial abilities of students will be tested with a different approach in the studies that will be conducted for this research. Moreover, taking the tests developed for this study as a starting point, researchers are recommended to develop tests on different disciplines and on different components of spatial ability.

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Chapter 5
Various Spatial Skills, Gender Differences, and Transferability of Spatial Skills

Lu Wang

5.1 What Is Spatial Ability?

5.1.1 Small-Scale vs. Large-Scale Spatial Skill

Spatial ability has been placed at the pinnacle of human intelligence (see Cattell 1971; Linn and Petersen 1985; Voyer et al. 1995). Spatial ability may be best construed as multidimensional (see Carroll 1993; Linn and Petersen 1985; Voyer et al. 1995).

However, definitions of spatial ability and ways to classify spatial skills have not been agreed upon. At a broad level, spatial ability can be divided into two major categories. For instance, McGee (1979) classified spatial ability as comprised of spatial visualization and spatial orientation factors. Kozhevnikov and Hegarty (2001) distinguished mental rotation from perspective-taking spatial skill (see also Huttenlocher and Presson 1973, 1979; Presson 1982; Wraga et al. 2000). Along the same line, Carpenter and Just (1986), Coluccia and Louse (2004), and Hegarty et al. (2006) used the terms spatial manipulation and spatial orientation to refer to the distinction between the two broad categories of spatial skills. Spatial manipulation has also been referred to as small-scale spatial ability in the literature (see Coluccia and Louse 2004; Hegarty et al. 2006; Kozhevnikov and Hegarty 2001; Lawton 1994; Pearson and Ialongo 1986; Quaiser-Pohl et al. 2004). Spatial orientation or perspective taking, on the other hand, has also been referred to as large-scale spatial ability. Large-scale spatial ability involves mental transformations along ego-centric frame of reference (or the central axis of one's body), whereas small-scale spatial skill involves mental transformations along allo-centric frame of reference (or the central axis of a reference object). The neural substrates implicated in the two

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spatial skills are the left parietal-temporal-occipital junction and the posterior parietal areas (with greater activation in the right hemisphere), respectively. Performance on large-scale and small-scale spatial skills as measured by psychometric tests typically has a small correlation. (Allen et al. 1996; Coluccia and Louse 2004; Hegarty et al. 2006; Hegarty and Waller 2004; Lorenz and Neisser 1985; Quaiser-Pohl et al. 2004), suggesting that the two categories of spatial skills are best treated as separate spatial skills.

5.1.2 Spatial Perception, Mental Rotation, and Spatial Visualization

Small-scale spatial ability can be further divided into three main sub-categories.

In two influential meta-analyses, Linn and Petersen (1985) and Voyer et al. (1995) reviewed studies using psychometric batteries to assess spatial skills and identified: (1) spatial perception, the ability to determine spatial relationships relative to the orientation of one's body (Linn and Petersen 1985); (2) mental rotation (or spatial relations), the ability to perform single-step mental transformation/rotation of two- or three-dimensional figures accurately in mind (Miyake et al. 2001); and, (3) spatial visualization, the ability to perform complex and multistep mental transformation/rotation (Miyake et al. 2001; Voyer et al. 1995).

Commonly used tests of spatial perception are the Rod and Frame Test (RFT) (e.g., Witkin et al. 1962) and the WLT (Inhelder and Piaget 1958). RFT typically require participants to place a rod vertically while viewing a frame oriented at an angle off the horizontal or vertical directions. The WLT requires subjects to draw or identify a horizontal line inside a tipped container.

The distinction between mental rotation and spatial visualization is not very clear-cut. The main distinction between the two spatial skills, as suggested by Linn and Petersen (1985), is that mental rotation involves rapid and accurate rotation of two- or three-dimensional figures, whereas spatial visualization involves multi-step manipulation of spatial information that does not necessarily have a time pressure. Delgado and Prieto (1997) argued that tasks measuring mental rotation and spatial visualization can be understood as rank ordered along a "speed/power continuum" or a "simple/complex dimension". Mental rotation tests tend to be "speeded and simple", whereas spatial visualization tests "occupy the other end" of the spectrum (Delgado and Prieto 1997). Another way to make sense of the distinction between mental rotation and spatial visualization is the extent to which either skill involves executive functioning. "Executive functioning" refers to the capacity to plan, to monitor and to control one's behaviors. The multi-step manipulations demanded by spatial visualization tasks and the possibility that more than one way to solve the problems is possible renders the capacity to plan for necessary steps ahead of time and to monitor one's thought processes during problem solving of importance. Tests that are typically used by spatial ability researchers to measure mental rotation skill include Card Rotation Tests (Ekstrom et al. 1976), Differential Aptitude Test—Spatial Relations, different versions of the classic Mental Rotation Test (Vandenberg and Kuse 1978; Peters et al. 1995), Primary Mental Abilities—Spatial Relations (Thurstone and Thurstone 1941), and other tests that resemble these tests in format and cognitive demand. Tests that are typically used to measure spatial visualization are Paper Folding and Surface Development, although occasionally, these tests have been used to measure mental rotation and some of the mental rotation tests have been used to measure spatial visualization skill. This illustrates the blurry boundary between mental rotation and spatial visualization skill.

5.1.3 Mental Imagery

Imagery research revealed four interpretations of the term “imagery”: (1) Imagery as a phenomenal experience to be experienced on a personal level and described in qualitative terms; (2) imagery as mental representations that can be studied experimentally; (3) imagery as a property of task stimuli; (4) imagery as a meta-cognitive strategy amenable to cognitive control (Richardson 1999). How imagery can be a personal experience and described in qualitative terms is illustrated by Blajenkova and colleagues’ (2006) work. The Object-Spatial Imagery Questionnaire (OSIQ), a self-report inventory to assess individual differences in visual imagery preferences and experiences (Blajenkova et al. 2006) aims at soliciting mental imagery that can be described in qualitative terms (e.g., vividness of imagery). Some of the items in this battery are “my mental pictures are very precise representations of the real things,” “I can close my eyes and easily picture a scene that I have experienced,” which treated imagery as a personal experience that can be described qualitatively.

Memory research is abundant with examples that illustrates imagery can be treated as mental representations subject to experimental manipulation. For instance, in a words retention experiment, mental imagery evoked by words is experimentally manipulated to examine the effect of mental imagery on memory recall. In this context, levels of imagery (i.e., high vs. low conditions) evoked by word meanings may be regarded as mental representations subject to experimental manipulation. Hegarty and Kozhevnikov (1999) study is another example of mental imagery being treated as mental representation, which delineated two types of mental representations, visual and spatial. Visual (object) imagery refers to mental representation of the appearance of objects. Spatial imagery refers to mental representation of the spatial configurations of object arrays. Imaging studies suggest that the neural basis of visual imagery is primary visual cortex and the neural basis of spatial imagery is the medial part of the intraparietal sulcus (see Mazard et al. 2004). Hegarty and Kozhevnikov (1999) study showed that regardless of levels of intellectual functioning, stronger spatial imagery/schematic representation was associated with better mathematics problem solving, whereas no such association existed between visual imagery/object representation and mathematics problem solving.

Using fMRI, Thompson et al. (2009) demonstrated further fractionation within spatial imagery—i.e., location imagery, which encodes spatial locations and transformation imagery, which encodes changes in orientation or mentally simulates such changes (Thompson et al. 2009). The neural basis of location imagery is near the occipito-parietal sulcus, medial posterior cingulate, and the precuneus and the neural basis of transformation imagery is near superior parietal lobe and postcentral gyrus (Thompson et al. 2009). The findings from imagery research parallel the working memory (WM) literature. Baddeley (1986), Logie (2014), and Cornoldi and colleagues' (1999, 2001) works showed that working memory can be fractionated into visual, static-spatial, and dynamic-spatial components. The alignment between the two types of imagery and the two components of working memory suggests that the two constructs are closely related. The connection between imagery and working memory makes sense when mental imagery is defined as mental representations being stored and processed in working memory.

The third and fourth definitions of mental imagery, imagery as a property of task stimuli, and imagery as a meta-cognitive process, received less attention in empirical studies. See Gyselinck et al. (2009) and Carroll's (1993) work, for an illustration of the fourth definition of imagery proposed by Richardson's (1999).

5.1.4 Working Memory

Working memory may be defined as a memory system that is responsible for the temporary maintenance and simultaneous processing of information that is required to complete complex cognitive tasks (Baddeley 1986). Prior research revealed a close relationship between working memory and general intelligence (Colom et al. 2005; Conway et al. 2003; Engle et al. 1999). In this section, a discussion of the distinction between short-term and working memory will be discussed. As well, a classic working memory model and its primary components will be introduced.

5.1.4.1 Short-Term Memory vs. Working Memory

The distinctions between short-term and working memories are nebulous. Therefore, some researchers have used the terms interchangeably. When distinctions are made explicit, short-term memory refers to the temporary storage function alone, whereas working memory, in addition to referring to the overlapping function with short-term memory, also encompasses the active processing function. This distinction is also reflected in tasks designed to measure short-term and working memories. Short-term memory is typically measured by simple span tasks, whereas working memory is typically measured by complex-span tasks. In addition to tapping simple storage, as measured by simple span tasks, complex span tasks also tap the domain-specific active processing function (Bayliss et al. 2005). Working memory, as measured by complex span tasks, has been found to be more closely related to academic achievement (Bayliss et al. 2005; Friedman and Miyake 2004; but see also Miyake et al. 2001; Shah and Miyake 1996 for a different view):. Miyake et al. (2001), however, reported correlations between complex span measures and the composite ability measures used in their studies to be no stronger than those between simple span measures and academic achievement; Shah and Miyake (1996), suggested spatial short-term memory and spatial working memory each contributed uniquely to spatial ability). These contradictory findings suggests further research is needed in delineating the nature of short-term and working memory as they relate to academic achievement.

Although both the short-term memory and working memory have limited capacities, they are limited in different ways. Working memory is limited by the amount of cognitive resources available within an organism to store and manipulate information pertinent to current tasks. Short-term memory, on the other hand, is limited by its storage constraint of between five to nine bits of information, if the input format is of auditory/verbal nature (Miller 1956). If the input format is of visuospatial in nature, the capacity limit is about four bits of information in healthy human adults (Luck and Vogel 1997; Vogel et al. 2001).

5.1.4.2 Two Competing Accounts of the Nature of the Working Memory's Capacity Limit

The nature of working memory's capacity limit is more complex than that of the short-term memory, which seems to be strictly confined to its storage limit. Some argued that working memory's capacity limit stems from a "trade-off" between the passive storage and active processing functions of the working memory. Resource-sharing model of working memory (Case et al. 1982; Daneman and Carpenter 1980), for instance, is based on the "trade-off" assumption. I.e., working memory's processing and storage functions compete for a limited pool of cognitive resources. On the other hand, a "task-switching account" postulates that the nature of working memory's capacity limit may stem from its attentional constraint in switching between passive storage and active processing functions (Towse et al. 2000; Barrouillet et al. 2004).

5.1.4.3 Visuospatial Working Memory

A number of studies showed that working memory and spatial ability are closely related across the lifespan (Levin et al. 2005; Gyselinck et al. 2009; Prime and Jolicoeur 2010; Kaufman 2007; Bacon et al. 2008; Shah and Miyake 1996; Miyake et al. 2001; Cornoldi et al. 1995). The connection between the two constructs may be understood in terms of cognitive load. Cognitive load of a spatial task refers to the limited pool of cognitive resources available to process visuospatial information. Thus, the cognitive load of a spatial task may be understood as the extent the spatial task taps the capacity limit of visuospatial working memory (VSWM).

Some (Logie and Pearson 1997; Hamilton et al. 2003) argued that further division is possible within VSWM. Evidence supporting further division is that visual and spatial components of VSWM develop at different rates. For instance, Della Sala et al. (1997) study showed that the visual component of VSWM, as measured by the visual pattern test (VPT) develops at a faster rate than the spatial component of VSWM, as measured by the Corsi blocks task (Corsi 1973; Milner 1971). On the other hand, using developmental fractionation technique, Hitch (1990), Hitch et al. (2001) and Klauer and Zhao (2004) found age-related changes in visual (object) component of VSWM develop at a slower rate than the spatial component of the VSWM (Van Leijenhorst et al. 2007). It should be noted that more than one way of classifying VSWM tasks have been proposed—e.g., along the dimensions of passive vs. active, simultaneous vs. sequential, and visual vs. spatial. The majority of studies investigating developmental changes within VSWM were drawn on the visual vs. spatial distinction. What is clear from existing findings is that further division within VSWM can be made based on the different developmental trajectories of those components.

5.2 Factors Contributing to Gender Differences in Spatial Skills

5.2.1 Gender Differences in Spatial Skills

There is ample evidence in support of gender differences in spatial skills (see Linn and Petersen 1985; Voyer et al. 1995 for two meta-analytical reviews). Gender differences in spatial skills emerge as early as 4 years and 6 months of age (Levine et al. 1999). Given the presence of multiple types of spatial skills, this section organizes the discussion of gender differences in spatial skills based on specific types of spatial skills defined in the previous paragraphs. Specifically, findings of gender differences are presented in the order of large-scale spatial skills, different types of small-scale spatial skills, and visuospatial working memory (VSWM). After describing these findings, factors contributing to gender differences in task performance identified in the literature will be discussed.

5.2.1.1 Gender Differences in Spatial Orientation Skill

Findings on gender differences in spatial orientation skill are mixed (Lawton and Morrin 1999; Coluccia and Louse 2004), with some studies show gender differences in favor of men and other studies show no differences or differences in the opposite direction. A female advantage in task performance, however, is rarely reported (Lawton 1994).

5.2.1.2 Gender Differences in Spatial Perception Skill

As noted earlier, Rod-and-Frame Test (RFT) and Water Level Test (WLT) (Piaget and Inhelder 1956, 1967) are typically used to assess spatial perception skill. Studies using these tasks consistently produced a moderate gender effect favoring men. However, gender differences in spatial perception skill are not comparable to gender differences in mental rotation skill in magnitude (see Linn and Petersen 1985; Voyer et al. 1995).

Water Level Test was designed to measure the development of an aspect of the Euclidean system of reference in children aged from 6 to 9. Piaget believed that this conceptual understanding should have been achieved by age 9 in most cases (Wittig and Allen 1984). Using three versions of the WLT (i.e., multiple-choice, drawing, and physical apparatus), Wittig and Allen (1984) found that even a number of adults failed the task. Error analysis showed that adults' failure differ from children under the age of 9. Since adults tend to err by choosing options with the slighted tilt (10 %) while children tend to draw water levels as either paralleling the sides or the bottom of the bottles, the researchers attributed errors made by adults as due to distorted perceptual system, rather than due to a lack of an understanding of the Euclidean coordinate system, as was likely to be the case with children. Wittig and Allen (1984) study showed that in the adult subjects they studied, gender effect was rather pronounced, with 40 % of women failing the task, compared with 17 % of men who failed the test.

It should be noted that spatial perception skill does not rely on vision exclusively several. Naylor and McBeath (2008) study, for instance, showed that both men and women relied on other sensory inputs in addition to vision when performing a spatial perception task and that the two genders rely on other sensory inputs to different degrees. Specifically, women rely more heavily on auditory information and men rely more heavily on visual cues. Future studies could more systematically investigate gender differences in spatial perception using stimuli involving multiple sensory modalities.

5.2.1.3 Gender Difference in Mental Rotation Skill

Males' advantage in mental rotation skill is well-documented (see Linn and Petersen 1985; Voyer et al. 1995). Men's advantage is most expressed in tasks with a time constraint, which may be due to men's comparative advantage in speedy rotations (Blough and Slavin 1987). However, even in the absence of a time constraint, men still outperform women on many versions of mental rotation tests. Gender differences persist even when the presentation mode switches from simultaneous presentation of target and choice items to two-alternative-forced-choice format. The latter format greatly reduces the cognitive load of a standard mental rotation test (Titze et al. 2008, 2010). Finally, when tactile stimuli are used, men still respond at a faster rate (Robert and Chevrier 2003).

5.2.1.4 Gender Differences in Visuospatial Working Memory

Findings on studies looking at gender differences in visuospatial short-term memory are mixed, with Capitani et al. (1991), Grossi et al. (1980), and Orsini et al. (1986) found a male advantage in task performance, and Kaufman (2007), Postma et al. (2004), and Vecchi and Girelli (1998) found no gender differences in task performance. These studies used various versions of Corsi blocks or simple span tasks to measure visuospatial short-term memory. On the other hand, studies using complex span tasks, i.e., tasks with both a passive storage and an active processing requirement, and n-back tasks generally revealed a male advantage (Kaufman 2007; Lejbak et al. 2011; Vecchi and Girelli 1998), with the exception of Duff and Hampson (2001), which showed a female advantage. The fact that gender differences in mental rotation in Kaufman (2007) study were completely mediated by gender differences in VSWM suggests that VSWM and mental rotation may be closely related constructs.

5.2.2 Gender Differences in Strategy Use

Aside from VSWM, strategy use also appears to play an important role in explaining gender differences in spatial skills (see Baldwin and Reagan 2009; Botella et al. 2009; Gluck and Fitting 2003). Existing data suggest that VSWM and strategy use jointly explain individual and gender differences in spatial skills (see Coluccia and Louse 2004; Bosco et al. 2004). Studies using VSWM tasks, large-scale spatial skills tasks, and small-scale spatial skills tests have revealed gender differences in strategy use.

5.2.2.1 Strategy Use Contributes to VSWM Task Performance

Evidence showing the presence of multiple strategies when solving VSWM tasks comes primarily from developmental studies and studies looking at expertise. Using children participants, Hitch et al. (1988) and Miles et al. (1996) revealed a change in how visuo-spatial information is coded in the developing brain as children grow older. Pickering (2001) noted that young children tend to rely on visuo-spatial coding exclusively when solving VSWM tasks, whereas older children also rely on verbal coding when tackling VSWM tasks (see also Van Leijenhorst et al. 2007). Thus, developmental improvements in VSWM task performance may be linked to the emergence of multiple representations, which enables older children to endorse multiple strategies to solve VSWM tasks.

Research on professional expertise suggests Professionals working primarily in visuospatial (e.g. architects) or verbal domain (e.g., writers) tend to have greater domain-specific working memory capacity in the domain they developed expertise in. For instance, Ericsson and Charness (1994)'s study showed how expertise in chess playing can stretch professional chess player's visuospatial working memory beyond the capacity limit of the average adult population. This phenomenon could be a result of professional chess players' years of practice, which enables them to develop efficient strategies to organize, store, and manipulate visuospatial information. Thus, expertise, i.e., years of experience working in a particular domain, may contribute to increased domain-specific working memory capacity (Cavallini et al. 2009) by ensuring more efficient usage of strategies.

5.2.2.2 Gender Differences in Strategy Use on Large-Scale Spatial Tasks

Strategies play an important role in explaining gender differences in performance on a variety of spatial tasks (Peña et al. 2008; Contreras et al. 2010). Reichle et al. (2000) found that when participants used cognitive strategies that are consistent with their cognitive strength (e.g., high spatial skills individuals adopting visuospatial strategies), they show less activation in areas of the brain related to that cognitive ability. Seen in this light, strategies may be a way of conserving limited cognitive resources (Contreras et al. 2010). However, only most recently, has strategy use become part and parcel of the spatial ability research program. This might be partly due to difficulties associated with correct identification of strategies and their quantitative evaluation (Contreras et al. 2010).

Gender differences in spatial orientation task performance may at least be partially mediated by strategy use (Bosco et al. 2004). Thus, it would be important to consider the contribution of strategy use when investigating gender differences in spatial orientation. Spatial orientation, as discussed previously, is a type of large-scale spatial skill. There is evidence that females favor "route strategy" when performing large-scale spatial tasks (Lawton 1994). This could be partially due to females' comparative advantage in memorizing locations, which may facilitate the identification of landmarks at crucial turning points of a route. Males, on the other hand, rely more heavily on "survey strategies", which utilize metric information (i.e., spatial configurations formed by objects in space) when performing large-scale spatial tasks (Coluccia and Louse 2004).

It has been suggested that survey strategy is more reliable and flexible, for it allows more flexible usage of routes, e.g., reversing the direction of travel (Lawton 1994). While individual landmarks inform travelers significant turning points along a route, they only explain one way of reaching the destination. On the other hand, survey strategies rely on the recollection of spatial configurations formed by several landmarks, which preserve the metric properties regardless of the direction of one's travel or the specific route selected (Lawton 1994).

A related question to gender differences in strategy use on large-scale spatial tasks that should be further explored is the basis of gender differences in strategy use. Since women have better location memory (see Postma et al. 1998; Iachini et al. 2005; Voyer et al. 2007), better location memory predisposes women to "route strategies," which depends primarily on recognition of familiar landmarks. It would also be interesting to examine whether there are developmental changes in the type of strategies favored by each gender when solving large-scale spatial problems.

5.2.2.3 Gender Differences in Strategy Use on Mental Rotation Tests

Strategies also play an important role in explaining gender differences in performance on mental rotation tests (Casey 1996; Geiser et al. 2008; Jordan et al. 2002; Peters et al. 1995). Due to the challenge of accurately assessing strategy use by relying on a single method, Gluck and Fitting (2003) proposed using multiple methods of measurement, which included response latency (time spent on looking at incorrect alternatives), response pattern analyses (inference of strategy use based on item difficulty), and error pattern analyses (inference of strategy use based on types of items incorrectly answered) to assess gender differences in strategy use. In the following paragrahs, studies that used different methodology to identify strategy use profiles are described.

Using a redrawn version (Peters et al. 1995) of the original mental rotation test developed by Vandenberg and Kuse (1978) and latent class analysis of response patterns, Geiser et al. (2006) identified five subgroups (latent classes) of solution strategies. The researchers also noted that the strategy class structure holds for male and female respondents. These solution class distinctions are justified on the basis of overall performance, speediness of response, and being spatial/non-spatial in nature.

Most commonly reported strategy distinction reported in the literature, however, is the dichotomized classification system that highlights the distinction between holistic and analytic strategies (Barratt 1953; Cooper 1976; Heil and Jansen-Osmann 2008; Strasser et al. 2010; Quaiser-Pohl et al. 2010). Within holistic strategies, Schultz (1991) identified two more subcategories: (1) rotating objects along their central axes, or endorsing the allo-centric frame of reference and (2) shifting perspectives or endorsing the ego-centric frame of reference to solve mental rotation problems. The nature of analytic strategies is more controversial. Some argued that they are essentially non-spatial in nature (Lohman and Kyllonen 1983; Geiser et al. 2006). Others (see Quaiser-Pohl et al. 2010) suggested that analytic strategies is a less efficient type of spatial strategy in that segments of, rather than the whole object, is rotated at a time. Thus, analytic strategies are sometimes labeled as "piecemeal" strategies (see Heil and Jansen-Osmann 2008). This classification system not only applies to the classic Mental Rotation Test (Vandenberg and Kuse 1978) and other varieties of mental rotation tests involving mentally rotating 2D or 3D images, such as the Cube Comparison Test (Janssen and Geiser 2010) and Picture Rotation Test (Quaiser-Pohl et al. 2010), but also to mental rotation tests featuring irregular-shaped polygons (Raabe et al. 2006; Heil and Jansen-Osmann 2008). Other strategy dichotomies that are sometimes used in lieu of the holistic and analytic strategy categories are the "bottom-up" and "top-down" strategy categories

(Butler et al. 2006). Top-down processing is effortless and efficient, whereas bottom-up processing is more effortful and time-consuming (Butler et al. 2006).

Gender differences in strategy use on mental rotation tests have also been identified from neuroimaging data. Using stimuli taken from a redrawn version of the Vandenberg and Kuse Mental Rotation Test (Peters et al. 1995) and the fMRI technology, Butler et al. (2006) found that the brain activation patterns differ between men and women as they make "same-different" judgments regarding whether the choice item is identical or different from the target item. Men activated primary sensory cortices, basal ganglia, and precuneus, which indicated "automatic and bottom-up processing mode. Women activated dorsal-medial prefrontal and other higher-order multimodal association regions, which indicated top-down and effortful mode of processing. This distinction in neural processing was also discovered by Clements-Stephens et al. (2009).

In sum, gender differences in strategy use on mental rotation tests can be inferred through neuroimaging data and by analyzing participants' response and error patterns. Holistic and analytic strategies distinctions may be seen as a continuum, which gives rise to more than two sub-categories of strategy classes (see Geiser et al. 2006) or as a dichotomy. in most cases, gender difference in performance favoring male is robust. However, it should be noted that it may not be the choice of a particular strategy per se, but rather, the number of strategies that are being used (see Strasser et al. 2010) that determines participants' performance on mental rotation tests. Strasser et al. (2010) study showed that as far as multiple strategy use is concerned, the more adept one is to switch between strategies, the better the overall performance. Future studies should investigate the interplays of multiple strategy use along the spectrum of holistic and analytic distinction in males and females.

5.3 How Are Spatial Skills Related to Mathematical Achievement?

5.3.1 Numerical Magnitude and Space

Quantitative and spatial skills are closely related (Holmes et al. 2008; Mix and Cheng 2012), perhaps at least partially due to shared neural coding between number and space in the brain (see Walsh 2003 for "a theory of magnitude"). There are numerous behavioral data that suggest mental representation of numerical magnitude is spatially coded. Number and space may be linked through an internalized mental number line (Dehaene 1997; Gunderson et al. 2012). The mental representations of number and space are highly automatized. Numerous behavioral studies demonstrated the robustness of the Spatial-Numerical Association of Response Codes, i.e., the SNARC effect (see Chap. 3, Handbook of Mathematical Cognition, edited by Campbell 2005, for a comprehensive review of these studies). The SNARC effect refers to the association of numbers with spatial left-right response coordinates.

5.3.2 Spatial Skills and Mathematical Achievements

Spatial skills are critical to achievements in the STEM areas (Shea et al. 2001; Wai et al. 2009). The association between spatial skills and mathematical achievements may be multifaceted. Kyttala and Lehto (2008) tested 128 students aged between 15 and 16 on several cognitive measures and found performance on the MRT (Vandenberg and Kuse 1978) to be highly correlated with measures of mathematical achievements. The predictive relationship between spatial skills and mathematical achievement is already evident at 3 years of age (Verdine et al. 2014). Aside from possibly sharing neural coding with numbers, spatial skills are predictive of how frequently higher-level strategies are used during mathematical problem solving. Finally, spatial skills may be linked to mathematical achievement through the meta-cognitive aspect of mathematical problem solving—e.g., endorsing effective mental imagery (Mix and Cheng 2012) to represent the problem space (see Hegarty and Kozhevnikov 1999).

There are individual differences in proclivity to rely on verbal and spatial processes to solve mathematical problems. Individuals can be classified as either “verbalizers” or “visualizers” based on self-reports during problem solving (Krutetskii 1976). Empirical studies conducted by Hegarty and Kozhevnikov (1999) revealed further division within visualizers: those who use schematic and less detailed spatial images during mathematical problem solving and those who use representational and detailed pictorial images during mathematical problem solving. These researchers found that those who utilized schematic representation tended to do better in mathematics than those relying primarily on pictorial representations during problem solving. It should be noted that socio-economic status (SES) may moderate the relationship between spatial skills and mathematics achievement. Astudy conducted by Casey et al. (2011) suggests that spatial skills were related to mathematics achievement in students from affluent communities but not as much in students from the low-income communities. Future studies should investigate the possible causes of this phenomenon. For instance, it may be that parents from the more affluent communities are more likely to provide learning experiences in their home environments that encourage the usage of spatial skills to solve mathematical problems, as suggested by Casey et al. (2011).

Given the predictive relationship between spatial skills and mathematics achievement, gender gaps in achievements in the STEM areas may at least be partially due to gender differences in spatial skills (Ceci et al. 2009). If spatial skills can be improved through interventions, then providing girls with extensive extracurricular activities or training to improve their spatial skills may reduce gender gaps in mathematical achievement. There is some evidence that women seem to benefit more from spatial skills training than men (Cherney et al. 2014). An earlier study by Ferrini-Mundy (1987) suggests that spatial skills training may improve women’s performance in certain areas of calculus more than for man. In the ensuing section, results from studies that sought to improve spatial skills through interventions, as well as results from studies that sought to explore the transferability of spatial skills training to mathematical achievement are reviewed.

5.3.3 Transferability of Spatial Skills Training to Mathematical Achievement

Ample evidence suggests spatial skills are malleable through interventions (Uttal et al. 2013). Spatial skills training can be effective in improving a variety of spatial skills as early as in kindergarten (Casey et al. 2008). Gender gaps in spatial skills have been reported to be reduced after such interventions (see Cherney et al. 2014). Comparing to boys, girls may benefit more from extensive engagement in enrichment program targeting spatial skills (Taylor and Hutton 2013).

There is also growing evidence for improving quantitative skills through spatial skills training (Cheng and Mix 2012; Sorby et al. 2013). Given the important role played by strategy use in explaining gender difference in strategy use, as reviewed in the previous section, it is reasonable to assume that instructing effective strategy use might also help reduce gender differences in spatial skills and possibly also gender gaps in mathematical achievement. There is already some preliminary evidence from Stieff et al. (2014) study. More intervention studies using randomized controlled trials to investigate the impact of strategy use intervention on spatial skills development and mathematical achievement are needed to establish the links between strategy training and gender gaps in spatial skills and mathematics achievement are needed. Future studies should also introduce multiple experimental conditions to compare the effectiveness between interventions targeting VSWM and strategy use with regard to the program's effectiveness in reducing gender gaps in spatial skills and mathematical achievement. With regard to the methods of intervention, there have been mixed findings concerning whether dynamic or static visualization tools are more effective in improving spatial skills (Froese et al. 2013). On the one hand, some studies found dynamic spatial visualization tools to be more effective, others found no differences between the two. Regardless of the direction of the finding, participants' levels of spatial skills probably need to be considered when comparing the comparative advantage of the two visualization tools. Future studies should systematically examine how levels of spatial skills interact with types of visualization tools in generating the most effective regimen for individuals with different levels of spatial skills.

Finally, it would be important to investigate not only the impact of short-term spatial skills intervention programs (e.g., programs of shorter durations) with intervention programs that last a bit longer (e.g., at least a semester) in terms of the immediate results, as well as long-term impact.

5.4 Summary

Various terms have been used to refer to different facets of spatial skills. This chapter attempts to clarify the conceptual distinctions among terms that have been used interchangeably in referring to a constellation of loosely defined spatial skills. In the first part of this chapter, distinctions between small-scale and large-scale spatial skills are drawn, followed by clarifications of spatial perception, mental rotation, spatial visualization, mental imagery, and visuospatial working memory, all of which may be regarded subcategories of small-scale spatial skills. In the second part of this chapter, studies reporting gender differences in various types of spatial skills defined in the first part of the chapter are reviewed, followed by a discussion of two main factors, i.e., gender differences in VSWM and strategy use, that contribute to gender differences in spatial skills. In the last part of this chapter, evidence supporting the intrinsic association between numerical magnitude and space, the predictive relationship between spatial skills and mathematical achievement, and evidence supporting trainability of spatial skills and transferability of spatial skills to mathematical achievement is reviewed. The chapter concluded by outlining future directions in spatial skills research.

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Part III
Research and Practices in Spatial Ability

Chapter 6
What Innovations Have We Already Lost?: The Importance of Identifying and Developing Spatial Talent

Jonathan Wai and Harrison J. Kell

6.1 Introduction

> We wanted flying cars, instead we got 140 characters. – Peter Thiel

In 1921, Lewis Terman initiated a talent search (Holahan and Sears 1995; Terman 1925) to find some of the brightest children in the U.S. His search for these "Termites" would identify a wide range of people, including some who would go on to be famous. These included kids who would become the educational psychologist Lee Cronbach and the creator of the TV show I Love Lucy Jess Oppenheimer. But there were two young boys who were not identified as gifted but eventually won the Nobel Prize in physics. Their names were William Shockley and Luis Alvarez and the scientific area in which they achieved their fame was arguably heavily visual-spatial in nature. Why were two Nobel winners missed? Likely because Terman had used the highly verbal Stanford-Binet, which did not include a sufficient spatial measure.

Peter Thiel (2015) famously said of the future: "We wanted flying cars, instead we got 140 characters." As innovative as Twitter might be, it pales in comparison to engineering feats that could truly transform our future. Think, for example, of the things Elon Musk has been dreaming about: the Hyperloop, a Mars colony, or a new energy source (Vance 2015; Wai 2015a). Vance (2015, book jacket) describes Musk as a "modern day alloy of Thomas Edison, Henry Ford, Howard Hughes, and Steve Jobs" – someone who has a mind like a computer and the ability to endure failure in his quest to change the world through his companies. As Dolly Singh, former head of talent acquisition for Space-X, told Vance (p. 220): "We *were looking for people*

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that had been building things since they were little." In essence, these are driven people who have extraordinary spatial talent, defined as "the ability to generate, retain, retrieve, and transform well-structured visual images" (Lohman 1996, p. 1000). But the people who have made it through the talent filter of one of Musk's companies are those who succeeded in overcoming many earlier educational and occupational hurdles. They are the students who had enormous opportunity to develop their spatial talent and succeed in traditional school systems that value students who are good at reading, writing, and doing math. For some of those spatially talented students that made it, they may have had parents to encourage those visual talents, even if school did not. They also may have had extremely high math and verbal abilities in addition to their high spatial ability, which allowed them to perform well in school even those weren't their primary strength. These individuals talented in all aspects may be more the exception than the rule, however, as people often favor either spatial or verbal ability (Humphreys et al. 1993) – even gifted individuals (i.e., those scoring in the top 1 % of cognitive ability). The average correlation between measures of phonological fluency and spatial aptitude is 0.4, meaning these capacities can develop unevenly – although it is certainly possible to score high on tests of both (Lohman 1994b; for a more technical discussion of ability intercorrelations see Kell and Lubinski 2013). Indeed, 70 % of individuals scoring in the top 1 % on spatial ability tests do not score in the top 1 % of verbal or math ability tests (Wai et al. 2009a). Further, spatially-gifted individuals seem to be relatively less able in terms of fluency and phonological word encoding, rather than verbal ability overall, with many exhibiting language delays or disabilities (Lohman 1994a, b). The implication is that there is a large population of spatially talented but less verbally and mathematically talented students who are not identified and therefore their talent is unlikely to be fully developed. *In fact, many standardized tests in schools today lack spatial measures*, and this means many spatially talented students are not being identified, and their talent is therefore unlikely to be fully encouraged or developed. Just how many Nobel Prize winning scientists or spatial innovators have we let fall through the cracks?

There is a large body of evidence linking spatial ability to educational-occupational outcomes (e.g. Gohm et al. 1998; Humphreys et al. 1993; Lohman 1994a, b, 1996; Smith 1964). However, this chapter focuses on a research study linking over 50 years of data to show that spatial ability in addition to math and verbal ability has predictive power in science, technology, engineering, and mathematics (STEM) domains (Wai et al. 2009a). Next, the issue of spatial ability training (e.g., Uttal et al. 2013a, b) and females in STEM are discussed. Then, how these findings and other research can be translated into education practice is presented (Wai et al. 2009b; Wai and Worrell 2016). Finally, a discussion of the broader societal implications of neglecting spatially talented students will be laid out (Wai 2013, 2015a). For example, how many innovations have we already lost because we have not adequately identified and developed the talent of some of our most promising innovators?

6.2 Historical Background

Spatial reasoning is associated with success in tasks classified as manual, mechanical, and practical (Carroll 1993; Hegarty 2004; Vernon 1950) thus by implication spatial ability's importance has been recognized for over 2000 years. Unfortunately, the history of prioritizing verbal and mathematical abilities over spatial ability is just as long. In Hellenic Greece and Medieval Europe, the physically-grounded mechanical arts (e.g., weaving, agriculture, masonry) were considered "illiberal", to explicitly contrast them with the intellectually-grounded "liberal arts" (e.g., grammar, logic, rhetoric) (Whitney 1990). This division continued through the Renaissance and into the Enlightenment – and was inveighed against in the first modern encyclopedia, where it was stressed that the liberal and mechanical arts should be considered on the same plane (Applebaum 1992; Diderot 1751/1992). Attitudes toward practical work were more positive in the early United States, where the Morrill Act of 1862 put aside land for the founding of major universities specifically emphasizing the teaching of "such branches of learning as are related to agriculture and the mechanic arts" (§ 304).

The nineteenth century also saw the beginning of modern psychology and the first scientific study of concepts related to spatial ability. Itard (1774–1838) and Seguin (1818–1880) devised form boards (now recognized as spatial skill measures) to facilitate the education of individuals with mental retardation (Sylvester 1913) while pioneers of psychology such as Galton (1880), James (1890), and Wundt (1896) all investigated or acknowledged mental imagery explicitly. Alfred Binet (1892) argued in favor of the existence of visual imagery and, as co-creator of the first intelligence test (Binet and Simon 1905), it contained items tapping spatial ability – as did many of its immediate American descendants (e.g., Goddard 1910; Terman 1916). Many mechanical and hands-on tasks were developed in the 1910s (e.g., Pinter and Paterson 1917) and by the 1920s scores on spatial tests were being used for a wide variety of purposes, including making decisions for awarding scholarships and personnel selection (Smith 1964; Viteles 1932); spatial tasks were even used to assess the mental capabilities of immigrants arriving at Ellis Island (Knox 1914; Richardson 2003).

Measurement of spatial ability has an especially long-standing history in the United States military. The Army Beta test, used to evaluate the mental competence of illiterate or non-English-speaking soldiers for service in World War I, included spatial items, as did the Army General Classification Test used in World War II (Humphreys and Lubinski 1996; Thorndike and Lohman 1990). The current entrance battery used in the United States military (Armed Services Vocational Aptitude Battery [ASVAB]) measures spatial ability through the Assembling Objects (AO) test – but AO scores are not included in the composite score (Armed Forces Qualifying Test) actually used to select soldiers in any branch of the military and only used for classification in the Navy (National Research Council [NRC] 2015). The NRC (2015) has recommended, however, that more attention be paid to spatial ability for the purposes of predicting performance.

6.3 The Importance of Spatial Ability for STEM Education and Occupations Across Half a Century

In this section, a number of prior studies and datasets that span over 50 years will be discussed to show the importance of spatial ability for STEM domains. These include a National Science Foundation report and review of the literature for pre-1957 (Super and Bachrach 1957), a stratified random sample of the U.S. 9th through 12th grade population spanning 1960–1974 (Project Talent; Flanagan et al. 1962; Wise et al. 1979) and data on the top 1 % of cognitive ability from the Study of Mathematically Precocious Youth spanning 1971 to the present (SMPY; Lubinski and Benbow 2006; Shea et al. 2001). Next, an examination within Project Talent data looking at earned degrees and the pattern of specific abilities compared to the general population and each other will be discussed. The section will conclude with a longitudinal examination of students in the top 1 % of spatial ability who were not in the top 1 % of math or verbal ability. This will constitute a concise summary of Wai et al. (2009a) which should be read in full for readers interested in technical details.

Over a half century ago, Super and Bachrach (1957) published a report titled *Scientific Careers*, in which they discussed the role of spatial ability in the eventual development and performance of individuals in STEM domains. This National Science Foundation report reviewed the literature to date, concluding that both mathematical and spatial reasoning were important for STEM and that “Longitudinal studies beginning at a relatively early age and extending over a period of some 10–15 years seemed called for” (p. 87).

Figure 6.1 shows longitudinal data from SMPY (Shea et al. 2001) illustrating how spatial ability, even over and above math and verbal ability, is associated with STEM disciplines and adds incremental validity in the prediction of educational and occupational criteria, even within a sample in the top 1 % of general cognitive ability. For example, each of the panels in Figure A illustrate math ability on the x-axis, verbal ability on the y-axis, and spatial ability on the z-axis for various major/occupational groups for four outcome variables: favorite high school course (Panel A), least favorite high school course (Panel B), college majors (Panel C), and occupation (Panel D). In order to explain how to read these graphs let’s look at Panel C which shows various college majors, and specifically at engineering, electrical. Because that group is to the right of the origin this group has above average math ability relative to other groups. Because that group is below the origin this group has below average verbal ability relative to other groups. And because there is a relatively long arrow extending to the right from that group’s location, this means this group has above average spatial ability relative to other groups. Now if we look within Panel C at humanities, we see the opposite pattern: below average math ability and spatial ability and above average verbal ability. For clarity, the STEM groups are within dotted line boxes, and what can be seen across all four panels is that within the SMPY sample, across high school course preference, college major, and

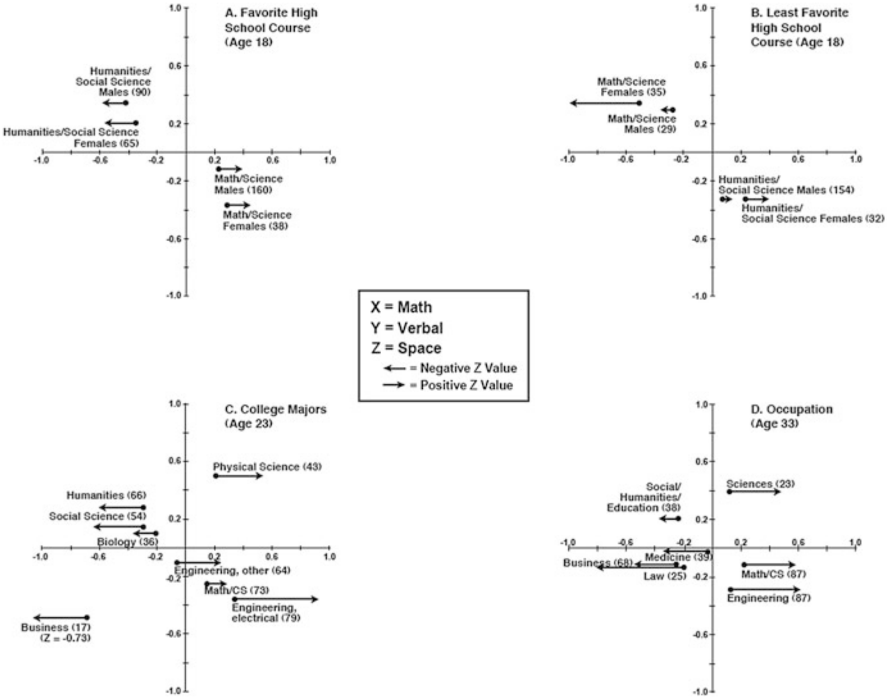

Fig. 6.1 Longitudinal data from SMPY
Shown are trivariate (X/Y/Z = Mathematical/Verbal/Spatial) means for (Panel **a**) favorite and (**b**) least favorite high school course at age 18, (**c**) college majors at age 23, and (**d**) occupation at age 33. Mathematical, verbal, and spatial ability are on the x-, y-, and z-axes respectively (*arrows* to the *right* indicate a positive z value; *arrows* to the *left* indicate a negative z value). Panels (**a**, **b**) are standardized within sex; Panels (**c**, **d**) are standardized across sexes. For Business in Panel (**c**), note that the length of the *arrow* is actually z = –0.73. *CS* computer science (Figure adapted from Shea et al. (2001). Copyright © 2001 by the American Psychological Association. Reproduced with permission)

occupation, the STEM domains tend to have higher spatial ability relative to the other groups.

Figure 6.2 shows longitudinal data from Project Talent (Wai et al. 2009a), a stratified random sample of high school students who were followed up 11 years after their graduation. At that time, their educational degrees and occupational status was assessed. Panel A shows terminal bachelors (i.e. a bachelors degree was their highest degree), Panel B shows terminal masters, Panel C shows doctorates, and Panel D shows occupations. Similar to Fig. 6.1, math, verbal, and spatial ability are plotted on the x-, y-, and z-axes respectively, and group means are relative to all other groups within each sample. Once again, across each of these panels, the STEM groups had relatively high spatial ability compared to the other groups. This replicates the findings from SMPY, a sample in the top 1 % in ability, within a stratified random sample of the U.S. population.

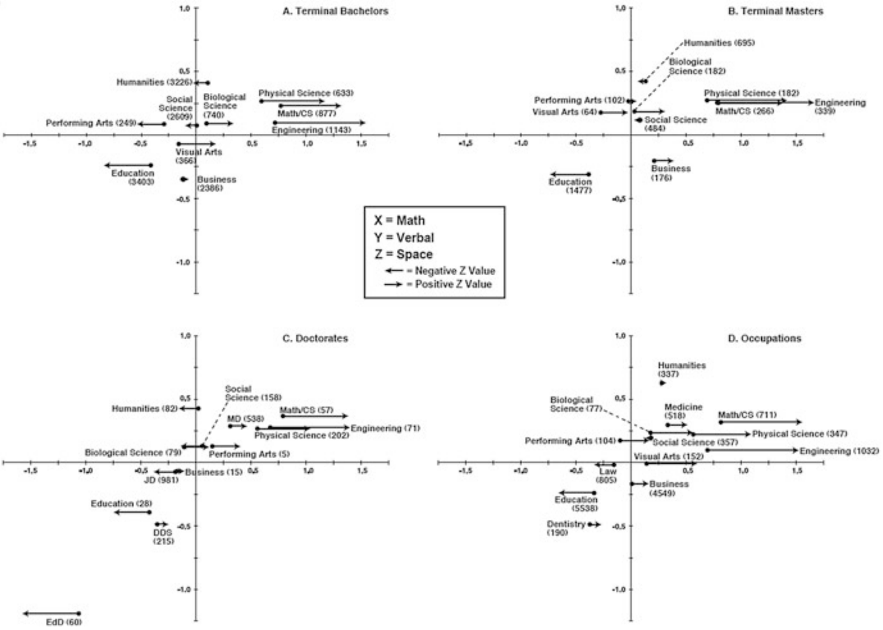

Fig. 6.2 Longitudinal data from Project Talent (1)
Trivariate means for Panel (**a**) bachelors, (**b**) masters, (**c**) doctorates, and (**d**) occupations of those individuals whose data were included in Panels (**a**–**c**). Panels (**a**) through (**d**) are standardized across sexes. Mathematical ability is on the x-axis, and verbal ability is on the y-axis; an *arrow* from each group mean indicates either positive (to the *right*) or negative (to the *left*) spatial ability. Breakdowns by sex are reported in Appendix B of Wai et al. (2009a). *CS* computer science (Data are from Project Talent (Figure adapted from Wai et al. 2009a. Copyright © 2009 by the American Psychological Association. Reproduced with permission)

Figure 6.3 also shows longitudinal data from Project Talent (Wai et al. 2009a), looking at terminal bachelors, masters, and PhDs by field. Instead of from a within groups perspective (see Fig. 6.2), it compares each of the groups to each other and to the general population on verbal, spatial, and mathematical ability as well as general ability (verbal + spatial + math). General ability is shown along the x-axis and specific ability pattern is shown along the y-axis each in z-score or standard deviation units. The first important thing to note is that each of these groups is well above average relative to the general population. For example, education (the lowest group) is over 0.5 standard deviations above average and the traditional STEM groups (math/CS, physical science, and engineering) are over 1.25 standard deviations above average (this pattern has been found for decades, for a review see Wai 2015b). This also shows there is a large average difference in general ability level across different groups. However, when we examine the specific ability patterns, the

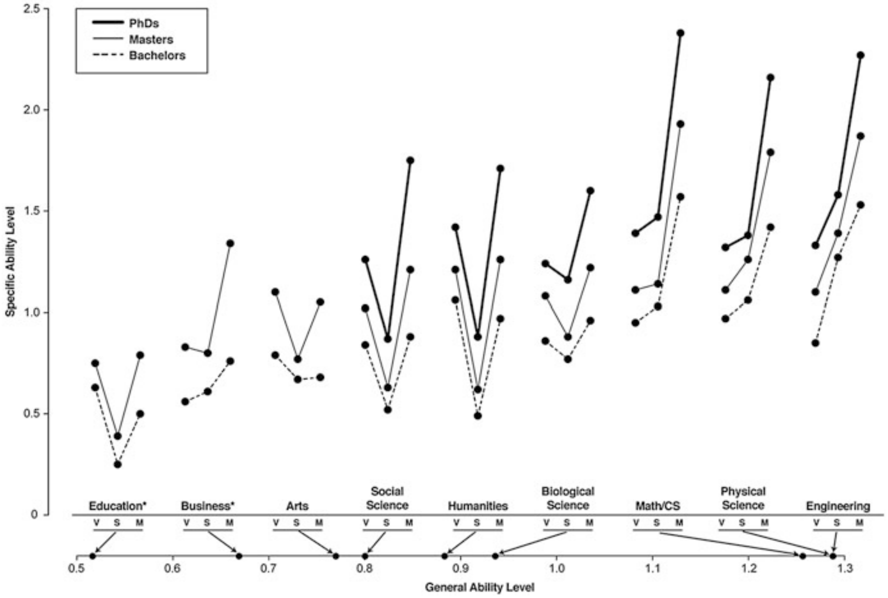

Fig. 6.3 Longitudinal data from Project Talent (2)
For education and business, masters and doctorates were combined because the doctorate samples for these groups were too small to obtain stability ($n < 30$). For the specific n for each degree by sex that composed the major groupings, see Appendix A of Wai et al. (2009a, b). Average z scores of participants on spatial, mathematical, and verbal ability for bachelor's degrees, master's degrees, and PhDs are plotted by field in Figure 3. The groups are plotted in rank order of their normative standing on g (verbal [V] + spatial [S] + mathematical [M]) along the x-axis, and each *arrow* indicates on the continuous scale where each field lies on general mental ability. All x-axis values are based on the weighted means across each degree grouping. This figure is standardized in relation to all participants with complete ability data at the time of initial testing. Respective ns for each group (males + females) were as follows (for bachelor's, master's, and doctorates, respectively): engineering (1143, 339, 71), physical science (633, 182, 202), math/computer science (877, 266, 57), biological science (740, 182, 79), humanities (3226, 695, 82), social science (2609, 484, 158), arts (615, masters + doctorates = 171), business (2386, masters + doctorates = 191), and education (3403, masters + doctorates = 1505) (Figure adapted from Wai et al. 2009a. Copyright © 2009 by the American Psychological Association. Reproduced with permission)

first thing to note is how general ability rises as we go from bachelors to masters to doctorates within each group (which is indicated by the dotted lines being below the solid lines being below the bolded lines within each field. Next, it's important to emphasize that the STEM fields have both spatial and mathematical ability higher than all other groups, but it's interesting to note that even their verbal ability is higher than that of other groups. Across the data reviewed in Super and Bachrach (1957) and in Figs. 6.1, 6.2, and 6.3, we can clearly see that spatial ability has operated consistently in predicting STEM outcomes for the last 50 or more years.

6.4 The Importance of Spatial Ability for STEM Creativity

Long-standing anecdotal claims about the role of spatial ability in making scientific breakthroughs hint at its importance extending beyond traditional educational and career outcomes and into the creative realm: Einstein, Faraday, Maxwell, and Tesla all reported that spatial imagery was critical to the formulation of their groundbreaking ideas (Lohman 1994a; Shepard 1978; Uttal et al. 2013a, b). Empirically, however, establishing spatial ability as a predictor of creative achievement in STEM is difficult. First, in order for people to be identified as creative they must *produce* something judged to be creative (Vernon 1989). This is a rare feat in fields as challenging as STEM (Wai et al. 2009a, b), meaning its base rate in the general population is low and necessitating large samples in order for a consistent (i.e., non-chance) association to be identified (Ackerman 2014; Meehl and Rosen 1955). Second, a long period of time is likely required between the assessment of individuals' spatial skills and the gathering of information about their creative products, as developing the content mastery and expertise necessary to make significant creative contributions is time-consuming (formalized as the "10-year-rule"; cf. Simonton 1991, 2003) – and also to remove the threat of reverse causality of some of the spatial skills developed in the process of creating those products influencing individuals' performance on the spatial ability test itself (Heckman and Kautz 2012). Third, in order to establish not only a link but also a *unique* link (i.e., incremental validity; Sechrest 1963) between spatial ability and STEM creativity, measures of cognitive abilities other than spatial ability are required, as the correlation among specific abilities could lead to STEM accomplishment being mistakenly linked with spatial ability when the association is contingent on a different ability (e.g., mathematical). A recent follow-up of the SMPY cohort featured in Shea et al. (2001) met these requirements.

Kell et al. (2013) studied the creative products of Shea et al.'s (2001) sample of 563 participants 35 years after their identification, when they were approximately 48 years old. They defined an accomplishment as "creative" in the terms set forth by Simonton (2012) and derived from the United States Patent Office: It is deemed novel, useful, and surprising (i.e., not obvious) by expert judges (e.g., patent reviewers, peer referees). They gathered information on participants' patents ($n = 33$) and peer-reviewed articles, the latter of which they sorted into three categories: arts/humanities/law/social sciences ($n = 27$), biology/medicine ($n = 35$), STEM ($n = 65$). Using the three ability scores obtained when participants were 13 years old, they used a two-step discriminant function analysis (DFA) to examine the extent to which the cognitive abilities accounted for variation among the four criterion groups. Entered at Step 1 of the DFA, mathematical and verbal scores accounted for 10.5 % ($p < 0.01$) and when spatial ability was entered at Step 2 it accounted for an incremental 7.5 % ($p < 0.01$) of the variance (18 % total). Further, the pattern observed in Shea et al. (2001) and Wai et al. (2009a, b) for educational and career outcomes was repeated for the creative accomplishments: Individuals holding patents or STEM publications exhibited ability profiles typified by spatial > verbal scores, while those holding publications in the arts/humanities, law, or the social sciences had profiles characterized by verbal > spatial scores (see Kell et al. 2013, Figure 1, p. 1834).

6.5 What Happens to People in the Top 1 % in Spatial Ability Who Are Not in the Top 1 % of Verbal or Math Ability?

A full 70 % of the top 1 % in spatial ability is not in the top 1 % of math ability or verbal ability based on population level analyses within Project Talent (Wai et al. 2009a; Webb et al. 2007). So these are essentially people who have the higher spatial and relatively lower math and verbal ability profile. In traditional talent searches, typically students with strengths in math and verbal ability are identified, and the schools are well equipped to provide challenge for students with these strengths, especially mathematical ability (Assouline et al. 2015; Lohman 2005), but likely less so for spatial ability (Wai 2012). Despite talent searches, teachers, parents, or others likely not identifying and hence not appropriately developing such spatial talent in the Project Talent sample, one interesting question is how these students who exhibit the high spatial but relatively lower math and verbal profile fare educationally and occupationally later in life. Figure 6.4 looks at STEM (top panel) and visual arts (bottom panel) degrees and occupations of that 70 % of the top 1 % that is lower in math and verbal ability. The sum of the black bars plus the gray bars for each category is the percentage of each group earning a specific outcome (e.g. for STEM male bachelors this was just over 15 %), whereas the black bars indicate the base rate in Project Talent for the respective grouping (e.g. for STEM male bachelors this was about 5 %), which indicates that relative to the base rate, these males earned STEM bachelors three times the base rate in the population. As can be seen across all other groupings, this pattern was found. Male and female comparisons in Project Talent are a bit dated, but are shown for descriptive purposes, so the main finding has to do with the overall pattern. Clearly there is a large pool of missed spatial talent that even though not being identified and having their talent developed properly as a group still goes on to accomplish highly in the STEM and visual arts disciplines. What more could they have accomplished if their talent was fully developed? Especially for females, this appears to be a missed opportunity to increase the STEM talent that so many U.S. reports have emphasized is needed (Miller et al. under review; PCAST 2012).

6.6 Spatial Ability Training and Females in STEM

A large number of researchers have targeted spatial reasoning training as a potentially fruitful area of research (Newcombe 2010; Miller and Halpern 2013; Uttal et al. 2013a, b; Sorby and Baartmans 1996, 2000), in part to potentially increase the

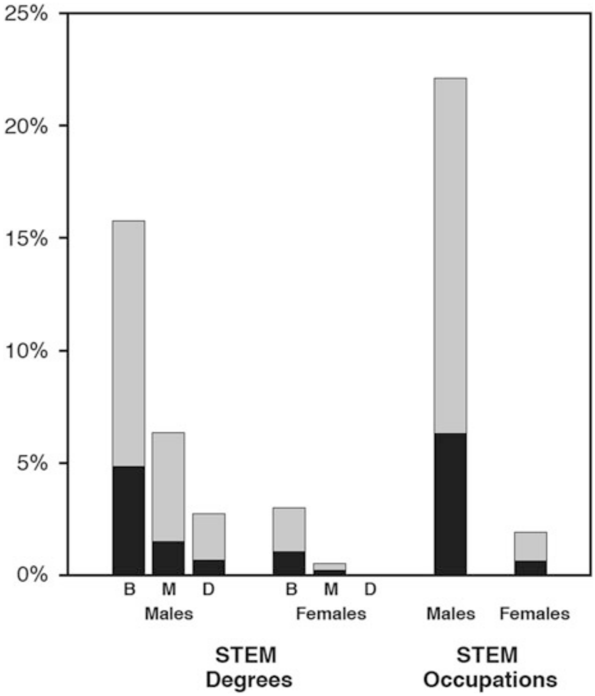

Fig. 6.4 Gender differences
The *top* panel includes (*left*) the proportion of the top 1 % in spatial ability who were not in the top 1 % in mathematical or verbal ability who earned STEM degrees and (*right*) occupations broken down by males and females, respectively. The *bottom* panel includes the proportion of this population who earned visual arts degrees and worked in related occupations. The *black bars* indicate the base rate in Project Talent for the respective grouping. *B* bachelor's degrees, *M* master's degrees, *D* doctorate degrees, *STEM* science, technology, engineering, and mathematics (Figure adapted from Wai et al. 2009a. Copyright © 2009 by the American Psychological Association. Reproduced with permission)

numbers of females in STEM fields but also to increase the number of STEM graduates generally. A major meta-analysis of spatial training studies by Uttal et al. (2013a, b) concluded that the average effect size for training relative to control was 0.47 (Hedges's g). And these findings are not just for the general population but also among gifted and largely STEM focused undergraduates (Miller and Halpern 2013). Uttal et al. (2013a, b, p. 352) concluded that "the results suggest that spatially enriched education could pay substantial dividends in increasing participation in mathematics, science, and engineering." Given the findings showing that a consistent STEM *educational dosage* or educational enrichment over a long period of time ends up predicting long-term educational and occupational outcomes (Wai et al. 2010), this may make sense and this area of research may be promising. However, it is important to make the distinction between training the *trait* of spatial ability and providing spatially enriched *education* to develop spatial modes of thinking in learning STEM or other subjects. At this point it appears that a number of experimental training studies show positive findings for training the trait of spatial ability, but not necessarily long-term evidence showing that this relatively short-term training is the *causal* mechanism that impacts later STEM educational and occupational outcomes as reviewed in this chapter (Wai et al. 2009a). Therefore, just as in other areas of training abilities, such as working memory or general intelligence (Melby-Lervåg and Hulme 2013; Shipstead et al. 2012), where the findings remain mixed despite a much larger literature devoted to the area, we don't know yet whether spatial training will pay significant dividends many years down the line and (if they do) exactly where. At the same time, for any students who have not been exposed to traditional spatial methods of thinking or hands on work, perhaps especially for females, familiarizing them with spatial modes of thinking and training those skills may be promising in increasing the number of females interested in pursuing STEM careers (Ceci and Williams 2010).

6.7 Spatial Talent Identification and Development

Given that the majority of standardized tests both in K-12 and those also used in college admissions and talent searches such as the Scholastic Assessment Test (SAT) and American College Test (ACT) don't include spatial measures, this means that spatially talented students are less likely to be identified as talented and therefore their talent is unlikely to be fully developed. Considering over half of the top 1 % in spatial reasoning abilities are currently being missed in modern talent searches (i.e., top 1 % in spatial but not in the top 3 % of math or verbal ability; Webb et al. 2007; Wai et al. 2009b), this means this population is definitely neglected in relation to other talented students, but also compared to students throughout the entire distribution of talent (Assouline et al. 2015).

6.8 Translating These Findings into Educational Practice

The findings reviewed and literature cited in this chapter show that spatial ability is linked to later STEM achievement and that as a whole spatially talented students and adults are being neglected (Lubinski 2010; Wai et al. 2009a). In addition, given that spatial ability is correlated lower with socioeconomic status in comparison to math and verbal abilities means that by using spatial ability measures we can capture more talented students from lower income backgrounds (Austin and Hanisch 1990; Wai and Worrell 2016). This can also help a population that may not have the support that other more fortunate students possess (e.g. parents that can help provide opportunities for spatial development that the traditional school system doesn't provide) (Wai and Worrell 2016). So what can we do to help translate what we know into educational practice?

Spatially talented students may be frustrated by how schools primarily emphasize the symbol systems of words and numbers (Gohm et al. 1998) and really the ability to speak, read, write, and do math (Wai 2011, 2013). Because some findings suggest that working in a “hands on” manner is important to this special population, for chemistry or physics classes one strategy might be to increase the time in the laboratory. Or when learning organic chemistry, students could be encouraged to create molecules in three dimensions during class using the standard kits. Robotics or architectural design courses might be introduced to encourage future engineers. Another research area suggests that reasoning with figures and shapes might help the spatially gifted learn subject matter. Thus when teaching a topic such as multivariate statistics to the gifted, the matrix algebra or geometric method might be used instead of traditional algebraic ones (Wai et al. 2009b). And even basic math could be taught in a primarily visual manner (Wai 2013). And to help spatially talented students increase their interest in reading, perhaps they might read biographies of famous spatially oriented and hands on scientists such as Thomas Edison (West 1991) or a current entrepreneur-engineer like Elon Musk (Vance 2015). The “maker movement” which encourages hands on projects and also things like FIRST robotics league may also be extracurricular activities that spatially oriented students might find helpful. In general, however, the key will be to find ways to increase both the spatial educational dosage for students (Wai et al. 2010) as well as look to factors such as teachers, administrators, parents, or really the larger educational culture not valuing students with spatial strengths and not understanding how creative they can be (Wai and Worrell 2016).

6.9 Broader Societal Implications: What Innovations Have We Already Lost?

In July 2015 NASA’s mission to Pluto became a success (Gebelhoff 2015; New Horizons 2015), and the scientific community was ecstatic. But what many don’t realize is that the project was to a large degree an endeavor that required incredible engineering and spatial ingenuity in addition to programming and other talents. In other words, spatially talented people played a large role. But just as the employees who make it through the talent filter for one of Elon Musk’s companies (Vance 2015; Wai 2015a), the NASA engineers who were a part of that project were likely dominated by people who had the opportunity to develop their spatial talent well into adulthood. There are many spatially talented kids (especially from low income backgrounds) who may not have similar support, and it is this neglected population, and the corresponding innovations that they might have already created for all of us (but did not have the chance to), that we should think about (Wai and Worrell 2016). When Peter Thiel pointed out that flying cars was the goal but instead we got Twitter, he made the point that innovation is not nearly where it could be. He argued that by focusing on things like apps on our smartphones, perhaps even one as widely used and arguably innovative as Twitter, is simply thinking too small. Indeed, despite the current era often being touted as one characterized by intense creativity, there is evidence the rate of major innovations is actually on the decline (Cowen 2011; Huebner 2005). Thiel's concern led him to create his Thiel Fellows program – which identifies talented young entrepreneurial minded kids (some of them spatially talented) – to jumpstart innovation for society. The research is quite clear that spatial ability is important for STEM and innovation and for our future. But because we have neglected this incredibly talented population, we may have already lost so many innovations, whether they come from Nobel Prize winners like Shockley and Alvarez, NASA's mission team to Pluto, or from engineering entrepreneurs such as Elon Musk. How many of these kids have we already let fall through the cracks? Perhaps it's time to focus on helping spatially talented students engineer our future so that we might have incredible things that are not yet imagined.

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Chapter 7
Empowering Visuo-spatial Abilities Among Italian Primary School Children: From Theory to Practice

Maria Chiara Fastame

7.1 Visuo-spatial Abilities in Early Childhood

Spatial cognition refers to "a branch of cognitive science that seeks to understand how humans and other animals perceive, interpret, mentally represent, and interact with the spatial characteristics of their environment" (Waller and Nadel 2013, p. 3).

A body of developmental studies starting with the Piagetian object permanence construct points out that since early infancy we learn to process visual (e.g., color, shape, texture) and spatial (i.e., position in the space) information. Indeed, a large variety of everyday tasks (e.g., exploring an unfamiliar city being driven by the information contained in a map) are based upon visuo-spatial information processing in order to create internal representations about the relationships between the moving individual and the elements located in the environment (e.g., the car is at *my* right) and independently of one's body position using the spatial information (e.g., distance, direction, orientation, location) of an object with respect to another one (e.g., the car is *near* the tree).

As widely illustrated, visuo-spatial perception and memory in infants are the precursors driving the successive development of action through the environment (e.g., Piaget 1954). That is, firstly the most relevant properties of the objects present in the scene must be visually and spatially processed in order to plan successful actions and then execute motor sequences to navigate into the spatial layout and to interact with its items (Gibson 1979). In this regards, Vasilyeva and Lourenco (2012) claim that spatial cognition is strictly related to visual processing, because if one has to remember the position of an item in the space, then he/she has to determine the shape and size of that object, therefore he/she has to think about side lengths and angles in order to understand its distance. A further spatial property being

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fundamental to interact with the surrounding world are the affordances, which "are defined by the fit between the environment and the actor", so that "the perception of affordances makes it possible to choose actions in a way that takes into account one's body dimensions and movement capabilities" (Fajen and Phillips 2013, p. 69). Assuming this theoretical perspective, since early childhood, the development of a spatial mental representation is based on the use of a reference point that can be viewer-dependent (i.e., *egocentric coding* based on the perspective of the observer) or landmarks-dependent (i.e., *allocentric coding* based on the use of external features being stable or moving through the environment).

Overall, it is assumed that in the first 6 months of life, spatial location is predominantly encoded with respect to the perspective of the observer (i.e., egocentric), such that by the age of 5–6 months toddlers learn to sit and rotate their trunk, so they can pay attention to and process the motion (McKenzie et al. 1984; Piaget 1954). Concerning this, Piaget (1954) argued that during the first 18–24 months of age infant behaviors are dominated by simple sensory and motor skills driving the interactions with the environment which lead to the construction of action-based knowledge of space. Assuming this, Piaget argues that spatial cognition is properly developed only in school age. In contrast, a contemporary tradition of research in the cognitive development field based on the use of sensitive experimental paradigms (e.g., habituation), points out that just after birth we learn to manipulate visuo-spatial information (e.g., depth, distance, size, position) in order to build our knowledge about the world and achieve immediate goals. Thus, it has been found that newborns display face processing skills, that is, they prefer to look at faces or clusters in which three blobs are located in an inverted triangle like the eyes and mouth of a human being than when these elements are located randomly (e.g., Johnson and Morton 1991). Similarly, according to Meltzoff and Moore (1977) newborns are also able to imitate the facial expressions of other people. Moreover, Caron, Caron and Carlson (1979) reported that 3 months old children preferred (i.e., they looked longer) stimuli changing in the size or shape (i.e., rectangular versus trapezoidal solids), whereas Quinn and Liben (2008) showed that children 3–4 months old can detect the familiarity of bidimensional stimuli that are differently rotated, suggesting that the sensitivity to rotation (i.e., a specific spatial skill) develops very early.

Similarly, there is evidence that infants 2 months old can solve object permanence tasks when a motor behavior is not requested, that is, recording the direction of their gazing it can be observed that children can anticipate the movement of a little train on the tracks both when the toy is hidden behind a screen (Bower et al. 1971) and when it is suddenly stopped before a screen (Bower and Peterson 1973). Besides, Baillargeon et al. (1985) found that infants 5 months old showed surprise when a little car running on a pathway continued to move beyond a screen when an obstacle (i.e., a trunk) was located on the pathway. According to the authors this shows that unlike Paget's theory (1954), children develop the object permanence concept in early infancy and not at the end of the sensory stage and that by 5 months of age infants are aware about the visuo-spatial properties of the stimuli located in the environment. Consistently with this, there is also evidence that infants 5 months old recall the position of an object previously seen, looking for that in a dark room (Shinskey and Munakata 2003). Moreover, at 5 months of age infants develop the ability to code and then process spatial distances in specific conditions, that is, they look longer objects being previously showed and then hidden in a long rectangular sandbox that emerge from a new location 8 or 12 inches away (Newcombe et al. 1999). Nonetheless, when the reference standard (i.e., sandbox) lacks, infants do not react with increased looking times to seeing the target objects located at differences distances (Huttenlocher et al. 2002). Taken together these studies suggest that before to navigate into the environment, infants use the information about the shape of the surrounding space to process the spatial property (i.e., distance) of a target stimulus.

However, a fundamental milestone for the development of spatial cognition is the onset of crawling at around 8–9 months of age, when toddlers start to explore more actively the environment, that is, they learn to manipulate visual and spatial representations using not only the egocentric coding system, but also the allocentric space one, in order to estimate distances and perform specific behaviors (e.g., reaching a toy) through their environment (e.g., Campos et al. 2000). In this regard there is evidence that infants exploring autonomously the environment can detect and process easily locations in relation to the elements present in that space than peers that do not craw/explore autonomously and rely upon the caregivers to move into the environment (e.g., Bai and Berthental 1992). In other words, the independent navigation of the environment let toddlers use the egocentric and allocentric spatial code systems, so that they realize that the position of elements surrounding them change continuously with movement and at the same time children develop the skill to update visuo-spatial representations of the features of the objects relative to the perspective of the viewer and to the relationship among the objects (i.e., allocentric perspective). Overall, this developmental achievement implies spatial updating, that is the ability to change one's representation of spatial relationships as a result of one's navigation through an environment.

Later on, children learn to develop further fundamental aspects of visuo-spatial cognition. Specifically, when children learn to walk, the capacity of navigating into the environment becomes gradually more refined, letting toddlers explore more actively the spatial layout connecting in a more refined way the 'what' and 'where' information (e.g., Clearfield 2001). This is very relevant for visuo-spatial learning, because children construct their knowledge about the properties of the world (e.g., softness, fragility, elasticity) interacting more actively with the elements present in the environment (e.g., throwing toys on the floor and then reaching them) and coding the location of objects with respect to stable cues perceptually available (i.e., coincident landmarks) or not perceptually present (i.e., distal landmarks). Concerning this, it has been documented that toddlers 16–24 months old can use coincident landmarks to search a desidered toy in a sandbox after that it is hidden by the experimenter and after that the infant is turned around in order to be disoriented so he/she fixes toward the object location (Huttenlocher et al. 1994).

However, a study by Mangan et al. (1994) suggests that a critical transition for the development of spatial learning is reached around the age of 21 months when toddlers can integrate multiple distal landmarks, such as distances and spatial relations among objects.

Later on, spatial representations can reach more complex levels when children 2–3 years old learn to run, to climb and explore the environment using other tools (e.g., bicycle). Indeed, there is evidence that when kindergarten children can actively move through an environment are more accurate in reconstructing a model town than peers that are passively stood in a position or those that explore the environment on a wagon (Herman et al. 1982). It means that the level of interaction with the environment can impact the way in which we represent it. That is, when visuo-spatial mental traces of the world become gradually more complex and rich, infants can graphically represent even objects being not physically present but that can be visually imagined. This developmental stage is reached when everyday functioning of children 2–3 years old is characterized by the development of the capacity to represent objects on paper, firstly scribbling with a pencil on a paper and later generating proper patterns of related signs to depict what one sees or imagines. According to Piaget and Inhelder (1956), drawing is an illustrative instrument that children use to represent their ideas about world. In contrast, during the 1970s and 1980s drawing behavior started to be thought as a complex and articulated cognitive task relying on perceptual, imaginative, constructive, symbolic behaviors, where what is depicted should represent the mental image of a real (e.g., a ball) or imagined (e.g., a smiling sun) object (e.g., Freeman 1980; Golomb 1973). Embracing this new theoretical perspective, spatial processing is a crucial aspect of drawing production, because how an object is thought impacts the way in which it is represented and even the sequencing of movements used to draw it (Vinter et al. 2008). Indeed, firstly one has to mentally represent and plan how to use the space of the sheet to carry out the figurative task, then he/she has to retrieve the mnemonic trace of the item to be represented and finally he/she has to depict the features of the object in the correct position (e.g., representing the human figure, the head has to be drawn over the neck, the legs must be traced under the trunk) in order to make the item recognizable. This implies that during infancy and later on, drawing skills become gradually more accurate as well as their underlying cognitive constructs, such as imagery, visuo-motor integration, constructive, mnemonic and executive functions. In this regard, studies conducted with atypically developing children (e.g., children with Williams syndrome) showed that those performing poorly on tasks requiring discrimination of shapes, visuo-motor integration, orientation and size judging abilities are also less proficient in tasks based on the reconstruction of geometrical shape or draw of pictorial stimuli (see Fastame et al. 2008). A related tradition of studies mainly embracing the neo-Piagetian approach shows that the development of drawing behavior is strictly related to the development of non-verbal working memory abilities, that is, the more units of mental images, visual and spatial information can be processed and temporarily stored in the immediate mnemonic system and the more the depicted objects in the drawings are accurate and rich of elements (e.g., Freeman 1972, 1980; Goodnow 1977; Morra 2008). In this regard, Morra (2008) claims that the spatial organization of a drawing is driven by systems of rules that are discovered in childhood through the drawing experience, such as representing tridimensional items on a bidimensional plan, using space to separate two items in order to avoid their overlapping, using specific strategies to represent the objects in a realistic way (i.e., including the partially occluded items). So, according to the author children need procedural and figurative schemes to be retrieved from long-term memory and temporarily maintained in working memory to represent the objects, as well as they have to rely on efficient perceptual processes (e.g., to detect the Gestalt principles) and executive functions (e.g., sustained attention, inhibition, planning). Morra (2008) concludes that the drawing quality is strictly related to the working memory capacity to store and process the schemes driving the visuo-spatial pictorial task, such that at 3 years of age only one scheme can be activated and temporarily retained, at 5 years two schemes can be used, whereas children 7 years old can rely on three schemes and finally 13–14 years old children can use and manipulate at the same time approximately six schemes in their working memory. This would explain why infant can only scribble to represent a familiar object, whereas at the beginning of the adolescence the respect of the tridimensional perspective becomes more evident and the depicted objects contains many details and can be easily recognized.

However, it is also worth pointing out that the development of non-verbal working memory is strictly related to the development of further daily activities involving spatial cognition, such as the mental reorganization of a pattern of objects in the environment (e.g., imaging to move some objects in a room), the mental reconstruction of a broken familiar item (e.g., reassembling the pieces of a puzzle). Thus, given the relevance of this topic, a short description of the architecture of visuo-spatial working memory and factors influencing its development will be presented in the next paragraph.

7.2 The Development of Visuo-spatial Working Memory in Early Life Span

One of the most accredited theoretical models about the architecture and functioning of the temporary mnemonic system was developed by Baddeley and Hitch (1974). These authors argued that short-term memory has to be thought as a multicomponent temporary system responsible not only for the immediate storage of a limited amount of information, but also it has to be considered as a cognitive medium able to work (i.e., processing) on the stimuli in order to carry out many daily life activities such as reasoning, orienting in the space, language comprehension. Within this theoretical framework, visuo-spatial sketch pad is posited as a slave component of the working memory, which is invoked in temporarily holding of verbal information being stored as visual images (e.g., the visual representation of a rabbit dressing a purple hat), as well as in storing and manipulating further types of non-verbal stimuli. Specifically, visuo-spatial sketch pad is fragmented onto a visual (i.e., responsible for the storage and processing of information such as the shape, color and texture of stimuli) and a spatial (i.e., serving to process the location of stimuli) stores, being functionally independent (e.g., Logie 1995; Vicari et al. 2007). Indeed, studies conducted both with normally developing children (e.g., 5–10 years old) and peers with genetic syndromes causing atypical developmental cognitive patterns (e.g., Williams syndrome) documented clear distinct developmental trajectories in visual and spatial working memory functions (see Fastame et al. 2008). Specifically, there is evidence that visual working memory (e.g., assessed in terms of number of known objects correctly recalled immediately after their presentations) is stable from 5 to 7 years of age but it increases significantly between 7 and 10 years. In contrast, significant differences have been found in immediate spatial recall tasks (e.g., immediate retrieval of positions located on a board in a scattered way) between 5 and 6, 6 and 7 and 7 and 10 years of age (e.g., Vicari et al. 2007). Overall, this empirical evidence highlights that non-verbal working memory performance is impacted by both the *nature* (i.e., visual versus spatial) and the *amount of information* to-be-remembered. Concerning the quantitative aspects of the visuo-spatial sketch pad, working memory capacity is usually assessed using span tasks requiring the immediate retrieval of items sequences (e.g., words, positions located on a board, figures of familiar objects) in the same presentation order. Numerous studies have provided converging evidence that the capacity of non-verbal working memory to temporarily retain and process visual and spatial information (i.e., span) develops with age from young childhood toward adolescence and by the age of 15 it tends to become stable and reach the adult efficiency level (e.g., Case 1985; Kail 1990). Several studies mentioned earlier (Huttenlocher et al. 1994; Mangan et al. 1994) showed that before 2 years of age the capacity of spatial working memory is very limited, because toddlers can explore the environment to actively search only a single toy being hidden a few seconds before. In contrast, Dempster (1981) documented that children 2 years old can temporarily hold and then recover approximately two units, whereas at the age of 5 memory span is approximately about four items, furthermore children 7 years old can immediately retrieve sequences of five stimuli and at the age of 9 the memory span is approximately of about six items.

Specifically, for what concerns the development of spatial working memory, at present there is a limited number of tools that can be used to assess mnemonic efficiency in preschoolers. Nonetheless, recently Baron et al. (2015) developed and normed a new test with good psychometric properties to rate spatial location learning and immediate recall in 3–6 years old children. The authors clearly showed that the immediate recall of objects located on a 3 × 3 grid varies as a function of the age of children.

Further empirical evidence on individual differences pointed out that within the spatial and visual components of working memory respectively, processes involved in the simple temporary retention of nonverbal items (i.e., *passive* mnemonic functions) can be distinguished by those (i.e., *active* working memory functions) engaged to process the stimuli thanks to the cognitive resources allocated by the central executive (for a review see Fastame et al. 2002). In this regard, a trend of research documented the impact of age-related factors both when typically developing schoolers (i.e., 6–14 years old children) were asked to temporarily retain spatial items and also when they had to manipulate visuo-spatial information to provide a non-verbal response (e.g., Kokubo et al. 2012; Myatchin and Lagae 2013). Moreover, studies conducted with children affected by Down syndrome showed severe difficulties when they were asked to carry out tasks requiring the active manipulation of visuo-spatial information (e.g., recalling a sequence of positional information in backward order), whether their memory performance was pretty similar to that of typically developing controls when the immediate recall of positions on a grid (i.e., passive spatial task) was requested (Lanfranchi et al. 2004).

Moreover, within the spatial working memory component, there is also evidence (e.g., Pazzaglia and Cornoldi 1999) of a dissociation between the development of the functions deputed to the immediate retrieval of stimuli presented simultaneously (e.g., the target positions to-be-remembered immediately after their presentation located on a matrix on a neutral grid, such as in the Visual Pattern Test by Della Sala et al. 1997) and those mnemonic functions driving the processing of spatial information presented in sequential order (e.g., target positions presented in a scattered way on a board that have to be retrieved in the same order of presentation such as in the Corsi Block Tapping task by Milner 1971). Following these suggestions and assuming a developmental perspective, Mammarella et al. (2006) conducted a study with differently aged children that were asked to carry out both visual, spatial and verbal working memory tasks, both passive and active ones. The authors posited that within the visuo-spatial working memory framework, one can distinguish an active visuo-spatial component (i.e., responsible for the manipulation of color, shape and position of the stimuli), a simultaneous spatial component and a sequential spatial subsystem.

A further trend of research has revealed that immediate recall performance for visuo-spatial information in children is impacted not only by the working memory capacity but also by the increase of information processing speed, which is more evident in early infancy and becomes slow thereafter (e.g., Myatchin and Lagae 2013). Nonetheless, at present it cannot be concluded whether the increased processing speed is due to a greater use of strategies by older children to process information or whether it depends upon the familiarity of the material to be processed (i.e., expertise). In this regard, Flavell et al. (1993) defined memory strategies as mental or behavioral activities being controllable, potentially deliberate and requiring a certain amount of attentional resources are carried out both at the encoding phase or at retrieval in order to achieve a purpose (e.g., recalling the position of some toys in the space). When differently aged children were asked to recall as many visual familiar items belonging to different categories (e.g., animals, fruits; furniture) as possible presented randomly, it was found that at pre-school age they could not consciously show strategic behaviors, even when they were explicitly trained to use memory strategies. Besides, the use of mnemonic strategies was not deliberate in kindergarteners and in young (i.e., 6 years old) schoolers, but their memory performance benefited from specific trainings (see Bjorklund et al. 2009). Thus far, this trend of results is consistent with further findings, indicating that when they were asked to recall pairs of figures. preschoolers (i.e., 4–5 years old) are able to use the “easily learned, easily believe” heuristic, according to which when they believed as easier to encode new pieces of information, then children predicted as more likely their ability to recall them in future. Nonetheless, at preschool age children cannot show explicitly the use of memory strategies to recall the visual stimuli. In contrast, the 8-year-old group showed a greater use of -effortful strategies to monitor the learning and then recall of the 24 picture pairs (Geurten et al. 2015). According to the authors the development of more strategic and explicit behaviors in memory performance of the schoolers were strictly related to the development of execution functions, which emerge predominantly around 7–8 years of age and are necessary to monitor, plan and inhibit the output responses.

Further studies have also documented the effect of knowledge on the immediate recall of visuo-spatial information. In this regard, a well-known experiment was conducted by Chi (1978) showing that children being expert chess players outperformed adults being beginners when they were asked to recall the positions pieces located on the chessboard. However, when the pieces were scattered randomly on the chessboard, the previous knowledge about the spatial information about the pieces could not influence memory performance. Thus, in this condition, the capacity limits of working memory was the factor impacting recall performance, that is, children recalled fewer spatial information than the novice one. A similar pattern of results was replicated when those participants were asked to recall sequences of digit-numbers immediately after their presentation (i.e., forward digit span task) in exact order: memory span of young children was shorter than that of the group of adult novice chess players. Overall, these findings suggest both that memory-span is influenced by the personal knowledge about the to-be-remembered stimuli and that memory-span is domain-specific.

Finally, a number of studies revealed that visuo-spatial working memory efficiency in childhood predicts other cognitive abilities including spatial problem solving, comprehension and several achievements in school (for a review see Conway et al. 2007). That is, children particularly able in the temporary retention and manipulation of visual and spatial information are also more prone to successfully carry out those cognitive tasks (e.g., mathematics) relying mainly on mental imagery, spatial reasoning processes.

With this in mind, a short overview of the main scholastic achievements being influenced by the development of visuo-spatial working memory functions will be illustrated in the next section.

7.3 The Impact of Visuo-spatial Working Memory Abilities at School

Since the 1990s of the last century, an increasing interest for the study of the visuo-spatial abilities in childhood highlighted its relevance for different topics at school.

Indeed, there is evidence that learning about geography involves the activation of inferential processes driving the processing of spatial information contained in the text. When the meaning underpinning the spatial description contained in a text is processed, the reader creates and then manipulates a mental image in which the elements are located consistently with the topographic information contained in the text book. That is, he/she relies on the efficiency of his/her passive and active nonverbal working memory process to succeed in the task. According to Tversky (1991) spatial descriptions can be presented assuming both a *route* and a *survey* perspectives (Tversky 1991). In the former, the spatial information about the items located into the environment is provided sequentially using left/right and forward/backward directions and landmarks, that is, reflecting the perspective of a person navigating into that physical space (i.e., egocentric code system). In contrast, in a survey perspective, spatial information is provided using the cardinal points (e.g., the Alpes are a mountain system located north of Mediterranean Sea, in southern Europe). These perspectives, together with visual working memory processes are also required when pupils use maps to learn about geography (e.g., distinguishing rivers and mountains relative to the colors with which they are depicted, learning about the position of a town in a region).

Moreover, as numerous studies (e.g., Gunderson et al. 2012; Li and Geari 2013) suggest, visuo-spatial sketch pad is also involved in mathematics achievement. Indeed, children attending elementary school learn different mathematical skills, including counting, digit numbers writing, written and mental calculation, symbolic magnitude judgement (e.g., comparing quantities or express judgements about parity), the manipulation of spatial images of number lines. Concerning this, there is evidence that the efficiency of visuo-spatial working memory functions in preschoolers predict mathematics achievement at school, that is, the visuo-spatial sketch pad is prominent for the processing of some aspects of numerical knowledge, such as manipulating visual images in order to mentally represent quantities on the number line, as well as for the creation of diagrams to solve word problems (e.g., Gunderson et al. 2012). Furthermore, Li and Geari (2013) documented that 6–11 years old children showing greater visuo-spatial working memory efficiency outperformed their peers in mathematics achievements at the end of the elementary school. This is consistent with a further studies carried out with first and third graders, showing that simultaneous (i.e., recalling routes) and sequential (i.e., tapping a series of positions located on a board) spatial working memory functions underlie number writing and quantity judgements performances (Simmons et al. 2012). Similarly, Kyttälä and Lehto (2008) conducted a study with a sample of adolescents showed that passive spatial simultaneous working memory is mainly involved in the solution of orally presented word problems, whereas passive spatial sequential processes contribute massively to performance on written word problems and finally active visuo-spatial working memory is essential for the solution of geometric problems.

For what concerns learning of geometry, the capacity to actively manipulate visuo-spatial mental imagery is essential to mentally represent geometric features (e.g., shapes, solids, size, orientation, location) on the sheet, both in tasks where the Euclidian principles can be used intuitively and in geometric academic problems, which are based on the use of symbols and are strictly dependent on previous education (see Giofrè et al. 2013). Furthermore, it has also to be noticed that proficiency in geometrical knowledge and efficiency in visuo-spatial working memory favor the gaining in learning about natural science, a scholastic topic implying an overt reflection on the features of the physical environment and mental imagery to represent it (e.g., Zhang et al. 2012). Indeed, intuitive observation and analogical reasoning skills (e.g., comparing two or more phenomena in order to extract common features and generalize some conclusions), together with the capacity to manipulate visual and spatial images drive the processing of hypotheses on the course of the natural phenomena, producing clear expectations about their possible physical changes, assessing the natural event object of study in order to verify the validity of the initial hypotheses.

Finally, from an educational perspective, the development of visuo-spatial sketch pad is also strictly related to the use of information technologies at school. Indeed, despite to the fact that nowadays digital learning technologies are widely used to promote school attainments in an innovative way, only very recently (Pazzaglia et al. 2008; Kornmann et al. 2016) it has been documented that spatial working memory is mainly engaged in the active exploration of the multimedia information (e.g., images, videos) to-be-learned. Indeed, Kornmann and coworkers (2016) found that navigational behaviors of materials displayed on hypermedia environments (i.e., an interactive learning approach based on the display of multimedia stimuli through tablet devices) were more effective in terms of learning outcome in fourth-grade schoolers being more skilled in temporarily retaining and manipulating complex spatial stimuli. Indeed, spatial working memory serves in a variety of multimedial navigational behaviors, such as representing and storing the main features of the digital environment in order to find similar items, representing and maintaining the navigational paths driving the learning of a given material, storing the path to return to explore it, focusing on relevant nonverbal material, ignoring the irrelevant concurrent ones.

Overall, the importance of visuo-spatial sketch pad in formal learning emerges mainly when the behavioral-cognitive profiles of children with visuo-spatial deficits are analyzed. In short, students with visuo-spatial disorder show a normal intellectual profile characterized by proficient verbal (e.g., vocabulary, reading) skills and scarce visuo-spatial resources (e.g., visuo-motor integration, attention, memory). Although a unique pattern of behaviors cannot be tracked, overall students with low visuo-spatial abilities, they are described as: (1) low proficient in sport activities, because of their scarce visuo-motor coordination and planning skills; (2) incompetent in spatial reasoning tasks and visuo-spatial problems (e.g., tasks based on mental rotation and estimation of distances), because of their reduced ability in manipulating mental images; (3) inefficient in written calculation, because of their scarce performance in putting numbers in columns according to their positional value (e.g., writing tens under tens); (4) unskilled in figurative and technical drawing tasks, because of their difficulties in mental imagery, low visuo-spatial attention and working memory, as well as specific deficits visuo-motor integration and visuo-constructional skills; (5) poor in geography and science learning (e.g., Rourke 1989; see for a review Fastame et al. 2008). Finally, Rourke (1989, 1995) described children with visuo-spatial deficits as affected by Non-Verbal Syndrome, a disorder also causing specific deficits in visuo-motor and tactile exploration and visuo-spatial sketch pad, as well as an evident difficulty in encoding nonverbal communication stimuli (e.g., facial expressions), that in turn is essential to develop social competence. In terms of development of spatial cognition, children with Non-Verbal Syndrome tend to lose themselves easily even in familiar environments and they need longer time to learn and recall new spatial paths (Lezak et al. 2004).

Numerous evidence-based studies suggests that typical developing learners and children with visuo-spatial deficits can benefit by the implementation of trainings aimed at enriching visuo-spatial abilities. In the next section, a psychoeducational computer-assisted and pencil-and-paper intervention developed to support nonverbal learning mainly in typically developing children attending elementary school will be presented.

7.4 How to Empower Visuo-spatial Abilities at School: An Educational Proposal

Numerous studies documented the efficacy of specific psychoeducational interventions aimed at enrich cognitive abilities mediating different academic achievements. In this regard, cognitive empowerment implies to provide children with opportunities characterized by novelty and complexity features to be handled in order to promote both learning about specific contents and learning about the metacognitive strategies necessary to monitor, regulate and control learning and memory (e.g., Mascia et al. 2015; Poon et al. 2010).

As pointed out by many authors in recent years (e.g., Chen et al. 2013; Fastame and Callai 2015; Holmes et al. 2010; Poon et al. 2010) information technology represents a further aid supporting successful academic achievements by the use of psychoeducational software. Concerning this, Holmes and coworkers (2010) defined computer-based psychoeducational interventions as *brain trainings*, that is, interventions aimed at empowering one or more cognitive functions (e.g., working memory) subserving scholastic attainments. Therefore, computer-assisted psychoeducational trainings let us provide individualized interventions where schoolers are actively involved to carry out the proposed cognitive tasks (Virvou et al. 2005).

It has been widely documented by a body of international studies that computer-assisted interventions alone or combined with pencil-and-paper ones are very useful to promote the empowerment of non-verbal cognition both in typically developing children and those with atypical cognitive-behavioral phenotypes (e.g., Beck et al. 2010). For instance, Poon et al. (2010) found the significant effect of a multimedia psychoeducational intervention aimed at promoting the development of visuo-motor coordination and visuo-perceptual abilities underlying learning about ideograms in Chinese children attending primary school. Moreover, Holmes et al. (2010)

found the effectiveness of a computer-based psychoeducational training developed to enrich verbal and visuo-spatial working memory in English schoolers.

For what concern the Italian context, with a colleague I developed a psychoeducational intervention aimed at empowering of visuo-spatial cognition in typically developing children attending the elementary school (Fastame and Antonini 2011). Specifically, the training includes both computer-assisted and pencil-and-paper tasks promoting the enrichment of different aspects of non verbal abilities, such as selective and maintained attention, visual and spatial working memory, mental imagery, visuo-motor coordination, non-verbal long-term memory. The pencil-and-paper tasks were developed in order to be directly proposed to single pupils, couples or groups of children (e.g., cooperative and inclusive learning) by the curricular teacher. Therefore, a secondary but important goal of those tasks is promoting the strengthening of social experiences among the peers through cognitive challenges. A further aim of the pencil-and-paper training is stimulating the child to reflect about what processes have to be engaged to carry out the nonverbal activities and how to control and monitor the results (i.e., metacognition). That is, the training intends also to promote the empowerment of the metacognitive skills implicated in the tasks that a student have to tackle at school. Instead, the computer-based activities imply a direct interaction between the child and an avatar driving the user in the tasks proposed and providing him/her an immediate feedback about his/her performance. However, it has to be noticed that a common feature of the computer-assisted and pencil-and-paper tasks by Fastame and Antonini (2011) is their playful nature, that is, they were developed in order to motivate the children to learn in an enjoyable fashion without having the idea to 'work' for the successful academic achievements. Recent empirical evidence suggests that the psychoeducational training by Fastame and Antonini (2011) is a useful aid to support the pedagogical choices of teachers and educators. Indeed, a recent study conducted with third and fourth Italian graders revealed that after 15 weekly sessions conducted in the classroom (i.e., lasting 60 min each) and in the multimedia room (i.e., lasting 30 min each), trained children outperformed controls in terms of speed of processing and verbal skills (Fastame 2014). Moreover, at follow-up, that is, after 6 months from the post-test, trained children were more able than controls in a mental rotation task requiring the active mental manipulation of spatial stimuli (Fastame and Callai 2015).

Finally, a further study conducted by Agus et al. (2015) showed that the combination of the pencil-and-paper or computer-assisted activities by Fastame and Antonini (2011) with a further mathematical training developed for Italian first and second graders is effective in promoting the development of written calculation skills in pupils 7 years old.

At present, further studies are being conducted in order to test the efficacy of my training controlling for different factors, such as the presentation modality of the materials (i.e., computer-assisted versus pencil-and-paper), the characteristics of the trainer (i.e., trained teacher versus expert trainer), the age of the to-be-trained children, the nature of the cognitive tasks (i.e., mathematical. Mental imagery, vocabulary) used in the pre-test, post-test and follow-up phases.

However, so far, it can be concluded that the psychoeducational program developed by Fastame and Antonini (2011) seems to be an useful tool to promote different achievements in elementary school.

7.5 Conclusions

Although the current chapter is far to treat the development of spatial behavior in an exhaustive way, it let us to track some conclusions.

First, unlike James's (1890) assumption, the infant's world is not made by a stream of unpredictable and confused information, as he postulated. Indeed, empirical evidence suggests that infants interact with their world, processing visuo-spatial information just after birth. This implies that in early childhood infants can represent specific visuo-spatial characteristics (e.g., size, shape, position) of their world, that is, they can temporarily store those mental objects' representations – if they are still available – to detect constant properties (e.g., shape) of the stimuli. In other words, unlike Piaget's theory (1954), since birth a very rudimental and gradually developing memory system works, driving infants in the construction of their knowledge about and interaction with the world.

A further conclusion emerging from this chapter is that the active exploration of the environment is fundamental for the successive development of further dimensions related to spatial cognition. Indeed, empirical evidence suggests that children being more actively involved in the exploration of the environment are more skilled in tasks requiring the manipulation of visuo-spatial information (e.g., creating a mental image of a navigated environment, solving mental rotation tasks). In contrast, children with low visuo-spatial abilities can verbally describe the environment but are inefficient in navigating into it and in mentally representing it (for a review see Fastame et al. 2008).

A further conclusion is that in order to represent and interact with the world, children have to rely on an efficient visuo-spatial working memory. Developmental studies on typically and atypically developing children revealed its complex architecture (i.e., visual versus spatial components; passive versus active processes) and its impact in many daily life tasks including different scholastic achievements. For this reason, for more than two decades greater attention is being paid on how to enrich visuo-spatial abilities to favor successful achievements at school. In this regard, in a digital world like the present one, where the interaction with the world of the new generations of children (i.e., digital natives) are driven by the use of information technologies (e.g., tablets and traditional computers, smartphone), multimedia devices have to be thought as a fundamental aid to promote the empowerment of visuo-spatial abilities especially in school age. That is, computer-assisted educational activities (e.g., cognitive tasks carried out by a software) have to be thought as a complementary support to the traditional curricular activities in order to favor the development of spatial learning and cognition and therefore to prevent unsuccessful academic outcomes (Fastame and Callai 2015). This implies the last but not least conclusion: from the one hand, spatial development is the result of a continuous interaction and therefore a reciprocal influence between the individual and his/her environment and from the other one the development of spatial cognition has to be thought as a continuous and reciprocal influence between the behavioral development dimension and brain maturation, that, in turn, is mediated bot by traditional pencil-and-paper educational activities and computer-based tasks (e.g., Herter 2009).

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Chapter 8
The Improvement of Spatial Ability and its Relation to Spatial Training

Yi-Ling Cheng

8.1 Introduction

8.1.1 What Is Spatial Ability?

Spatial ability is the ability to process spatial thinking. The definition of spatial thinking can be found in a recent article published by Newcombe and Shipley (2015). They concluded that findings from neural, cognitive science, and linguistic studies suggest that spatial thinking is using spatial information for "manipulating, constructing, and navigating the physical world" (page 2). Such a thinking process can be characterized as a cognitive ability and thus can be ordered along a continuum scale from low to high levels of spatial thinking. Therefore, a person who possesses a high degree of spatial thinking is a person who has high spatial ability.

The benefit of possessing high spatial ability has been identified in previous studies. Many studies have established that people who possess high spatial ability also have a higher likelihood to be successful in professional careers in science, technology, engineering or math (STEM) fields (see reviews in Levine et al. 2016 or Wai et al. 2009). High spatial ability also plays a critical role for surgeons (Wanzel et al. 2002), dental education (Hegarty et al. 2009) or even being creative (Kell et al. 2013).

These possible benefits have led to continuous attempts to precisely measure, identify high spatial ability and further improve spatial ability to see if training on spatial ability can improve STEM domains (see discussion in Newcombe and Frick 2010; Uttal and Cohen 2012; Mix and Cheng 2012). Through these attempts, a number of spatial abilities were identified and measures of these spatial abilities were developed accordingly. However, several debates exist among the ample

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amount of research on the studies of spatial cognition and spatial abilities. One line of debates is whether there is a single spatial factor or multiple spatial factors existing in spatial abilities. Specifically, this questions whether all spatial tasks measure the same construct or if different spatial tasks measure related but distinct constructs. Another debate in the research is whether spatial training can be generalized to other cognitive abilities. Specifically, to produce near transfer, which is the transfer effect to other untrained spatial abilities task, or to produce far transfer effect to STEM field, which is the transfer effect to another construct.

Although these two debates seem to be directed as two different questions, they are in fact deeply connected. Studies on cognitive training studies have presented how training a shared cognitive skill/component produced the training- transfer effect to structural dissimilar tasks (Karbach and Kray 2009; Schubert et al. 2014). If all spatial tasks measure the same construct, training on one spatial task should be easily transferred to other spatial tasks. On the other hand, if each spatial task measures a different construct, training on one spatial task might not transfer to the spatial tasks measuring different constructs. This mechanism will also further influence the possibility of improving performance in STEM domains. Therefore, the distinctions of spatial abilities are important from both theoretical and practical standpoints.

8.1.2 The Categorization of Spatial Abilities Tasks

Attempts to categorize these spatial tasks have made by many previous studies with different approaches. Linn and Petersen (1985) tried to categorize spatial abilities as spatial perception, mental rotation, and spatial visualization; methodologically they identify these from both psychometric approaches and underlying cognitive processes. Along the same lines, recent work by Uttal et al. (2013) and Newcombe and Shipley (2015) further proposed a two-by-two typology using recent findings from cognitive science research. The two-by-two categorization maps out static/dynamic processes with intrinsic/extrinsic processes to generate four different spatial dimensions (i.e., intrinsic static, extrinsic static, intrinsic dynamic, and extrinsic dynamic). Although this theoretical approach reflects the research from cognitive science nicely, there have not been any studies to test whether this typology verifies the cognitive structure of spatial ability empirically. Several difficulties for categorizing spatial abilities in previous research have been identified. For example, Lohman (1979) has reviewed and discussed extensively the nature of factor analysis on spatial abilities studies and how it might have led to inconclusive results, as different studies have used different spatial tests to refer to the same spatial constructs. A second issue is that the study of the structure of spatial ability has mainly been done with factor analysis. The results of factor analysis has to do with whether a sufficient number of measurement variables were involved in the analysis. For example, Fabrigar et al. (1999) suggested three to five tasks for each factor is adequate to get a decent result. For example, if a researcher is using the two-by-two typology mentioned above with at least three tasks in each category, a total of 12 spatial tasks would need to be included in order to correctly identify spatial categories. Furthermore, the accuracy of categorization of spatial measures is critically related to whether the selected measures have adequate validity and reliability in terms of their representation of the constructs that they intend to measure.

Fundamentally, the validity and reliability of spatial measures are important for identifying the cognitive structure of spatial ability for effective training, especially because increased scores of spatial measures is used as an indication of effective spatial training. The purpose of this chapter is therefore to review spatial tests from a modern psychometric perspective and provide new insights for future training studies. Although many different spatial tasks have been developed over time, the current chapter focuses on the constructs of spatial ability that have been extensively applied for further training studies in previous studies. Also, to help readers to create a mental map of the structure of spatial ability with these spatial ability measures, these tasks will also be discussed within the framework of 2×2 typology and Linn and Petersen's work as well.

In the following paragraphs, the representative spatial measures of the constructs and the validity and reliability of these measures will be discussed first. The validity and reliability of the measure then will be discussed alone with the existing individual differences. This is because any individual differences are important for the purpose of identifying whether the same construct is measured across different populations (e.g., gender or cultural differences). After the analysis of the characteristics of these measurements, the generalizability of its training effect will be discussed and interpreted.

8.2 Overview of the Spatial Tasks in Spatial Training Studies

Among all spatial training studies, several types of spatial measures have been applied more comprehensively in previous training studies. These are: water level task, mental rotation, visual spatial working memory task, and map reading task. Each of these tasks is described in detail in a separate section below. To help the reader understand each task, in the beginning of each section, the test characteristic of the specific spatial test will be explained first. The test development, the item description, the test instruction, and the range of item difficulty will then be described and explained. Next, the validity and reliability in previous studies will be reviewed. The reliability will be discussed first as reliability is prerequisite condition for validity (Thorndike 1997). The primary reliability to be reported here is test-retest reliability, which is the correlation between two testing time points with the same test. If the test-retest reliability was not established by a previous study, Crobach's alpha reliability (internal consistency) or split-half reliability would be provided instead. When the performance on spatial tests is assessed using the judgments of raters, an inter-rater reliability will be identified. For validity, the dimensionality of the test will be identified first. The concurrent and discriminate validity will be discussed after that. Finally, the ways in which improvement of these spatial tasks were used as indications of effective training would be discussed.

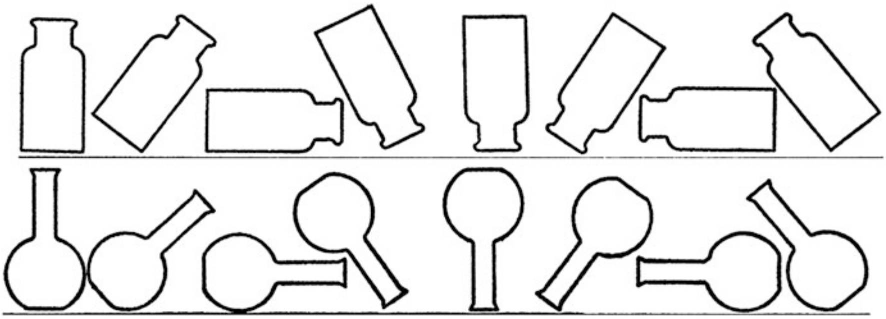

Fig. 8.1 A sample water level task item (Beilin et al. 1966, p. 326)

8.2.1 *Water Level Task*

The water level task was first developed by Piaget and Inhelder (1956) for understanding children's concept development of the Euclidean reference system. To administer the test, subjects were first shown pictures of titled empty bottles and then were asked to indicate (by drawing) the water level on these titled pictures. To be able to respond to the questions of the water level task correctly, the participants needed to understand and apply the invariant principles (see Fig. 8.1 for the example of the task). The invariance principle is the concept that objects remain unchanged when some transformation is applied to the objects. Specifically, in the water level task, the invariance principle means that the subjects need to understand that the water level should be horizontal despite of the changing angles of the bottles. The item difficulties changed with the different angles of titled bottles such that larger angles were indicated to be harder items (Vasta et al. 1994). Previous studies also have discussed whether the round shaped bottles or square shaped bottles are more difficult (e.g., Liben 1978; Vasta and Liben 1996; Wittig and Allen 1984). While one might hypothesize that round shape of bottles should be easier as it might create less confusions with the horizontal frame of the task, the results from previous studies did not confirm that.

In previous studies, participants were asked to produce two types of responses: reproduction and recognition. For reproduction, the subjects needed to generate the drawing of water level. For recognition, subjects were asked to pick an answer from multiple-choice items (Wittig and Allen 1984). Because recognition might produce a 20–25 % guessing rate (depending on the number of choices given), reproduction of the lines might be more precise for estimating the underlying ability.

8.2.1.1 Validity and Reliability

Wittig and Allen (1984) have computed Spearman-Brown reliability using different versions of water level tasks and identified different reliabilities between males and females. These tasks were categorized with the combination of three response methods (Draw vs. Multiple choice vs. Apparatus (using real bottles)) by two types of bottles (round vs. rectangle). The lowest reliability is found to be with the items that ask for drawing of rectangle bottles. For this condition, reliabilities are 0.78 for males and 0.83 for females, whereas the other conditions have reliabilities ranging from 0.86 to 0.96 across males and females. Other studies using the water level task have also found high reliability using Cronbach's reliability. For example, Cronbach's reliability ranges from 0.80 to 0.86 (Li 2000). These reliabilities also did not differ much between male and female, suggesting an overall good reliability.

In terms of dimensionality of this task, the Rasch item response model was found to fit this task well when using a mixture of 431 children and adults (Formann 2003). Formann (2003) suggested that this implies the unidimensionality of this task. However, Kalichman's (1988) analysis found that there are four sub-abilities: "visual perceptual skills, mental imaging and rotation skills, utilization of spatial coordinate system, and recall of relevant information" (p. 273). These sub-abilities seem to imply the existence of multidimensionality within the water level task. Although these results seem contradictory, it was demonstrated that multidimensional data could also fit well with unidimensional models when items measuring the same composite of abilities are used (Reckase et al. 1988). Therefore, it is possible that the water level task can be a multidimensional task that still fits a unidimensional model well.

In terms of its spatial category, the water level task belongs to the extrinsic static category in Uttal et al.'s typology (2013). Extrinsic static is defined as "understanding abstract spatial principles, such as horizontal invariance or verticality" (Uttal et al. 2013). Specifically, to be able to compute correct responses in the water level task, subjects need to refer to an extrinsic frame. The visual image was not transformed during the task performance, and it only requires static imagination.

However, the discriminant validity of this task has shown some different directions. Some studies showed that the water level task has low correlations with other spatial tasks, but also was indicated to have significant positive correlations with the mental rotation task and embedded figure test in previous studies (Signorella and Jamison 1978). One possibility could be that for generating a correct response, the subjects need to recruit several congitive processes such as transforming the image of the volume of water to align with the reference system. Therefore, evidence also shows that a larger angle of the bottle produces more errors compared to a small angle of the bottle (Vasta et al. 1994) as it would require more efforts. Neural evidence also indicated that people who perform well on this task and the mental rotation task both show similar advances in brain lateralization in the right hemisphere (Rilea et al. 2004), suggesting both tasks are similar in brain lateralization. Perhaps this is also the reason that although the water clock and plumb line tasks both require people to understand the invariance principle, there is little evidence of transferability between the water level and plumb line tasks (e.g., Vasta et al. 1996).

Furthermore, these different sub-abilities might develop at different rates that might be a reason that performances differ in different subgroups (such as males and females or different age groups; Thomas and Turner 1991). For example, while

Pieget indicated that children should develop their understanding of invariance principle around age 9 and therefore perform this task at ceiling, some studies have found that even college students were not able to perform this task well (e.g., Liben and Golbeck 1980; Vasta et al. 1996). There are also gender differences favoring males (e.g., Vasta et al. 1996) and cultural differences were also found favoring Chinese (Li 2000). The gender differences might be likely due to the difference of right hemisphere advances (Rilea 2008). The cultural differences might be due to the possibility that learning Chinese is itself a process of spatial training (e.g., Li et al. 1999). Further studies are needed in studying the measurement invariance of this task across cultures and gender. Overall, these different results might indicate measurement variance in different populations and therefore the interpretation of results in different cultures and genders should be done with caution.

There are several factors might influence the reliability and validity of water level task. For example, the length of water level task is varied across different studies is one of the factors influencing the reliability. Some studies used 12 items (each of them 30° apart) and some used 8 items. Though the item difficulty was varied with different angles, one might wonder whether this is really necessary to assess individual performance of understanding a single principle. For example, in Tran and Formann (2008), the participants' responses were mostly either 0 or 8 across life span (see Fig. 8.2, adapted from table 1 score distribution from their paper). Such a response pattern suggests a possible bimodal distribution of the score range. This distribution might be an indication of discrete attributes. Based on this bimodal distribution, the reliability would therefore be high. Different versions of the water level task might also be confounded with the item difficulty. For example, in the version of square shaped bottles, the titled angles of 90 and 180° should probably be removed as the reference frame is paralleled with the bottom of the bottle, which causes the confusion of interpreting whether subjects answered these two items correctly based on true understanding of invariance principle or they were using the bottom of the bottle as the reference system.

The method of scoring the water level task might also create a threat of its validity. Specifically, researchers often set a certain degree of tolerance level (such as 4 or 5° of deviation) to judge whether the items were correct and add these up to a sum score without further evidence to support why a certain degree was chosen as the cut off criteria. A possible cut off value could be done by having follow-up questions assessing whether participants truly understand the invariance principle and then calculating the deviation degrees only among participants who do understand the principle with computing the standard errors from such deviations. This might provide support for a particular cut off degree for the scoring process. Other than using a sum score, researchers also calculate the exact degree deviation to estimate the performance of subjects (e.g., Vasta et al. 1996). Specifically, by using the deviation of the angle from the horizontal level, the score is estimated with the degree of variation between the participants' response and reference horizontal line. However, considering the possibility that a person with 10° deviation might not have understood more about the invariance principle compared to people had 100°

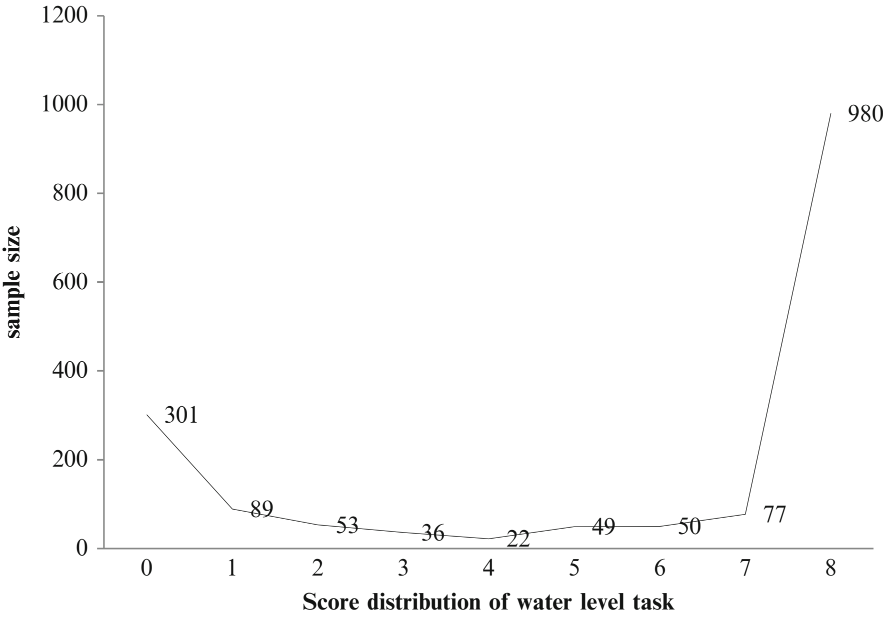

Fig. 8.2 The overall score distribution of water level task (Adapted from Table 1 in Tran and Formann 2008)

of deviation, a summed score might not less differentiate individual level of performances compared to using deviation scores.

8.2.1.2 Training

Improvement

Several approaches have been developed to improve the performance of the water level task and they were all shown effective results. One of the major approaches is using observation (or experience) training (Krekling and Noedvik 1992; Smedslund 1993; Vasta et al. 1996). The results show significant improvements, though Smedslund (1963) noted that observation training has almost no effect on people who did not answer any items correctly in the pretest phase, suggesting the training might not work on people who have no understanding of the invariance concept.

Another approach that might overcome this shortcoming is using instructional approach. By explicitly explaining to the participants what is the invariance principle, the research hopes to see participants understand and apply the concept directly in the task. For example, in Li's (2000) study, the instruction was to remember that no matter how the water bottle was rotated, the water level is always horizontal. The improvement was also significant, though it was difficult to identify whether the participants really understood the principle or simply memorized the principle.

Some individual differences were also found from training effects. For example, there were some age differences revealed in the training results. For example, in Li's (2000) study, the training effect was only significant for 6th and 8th graders but not for 4th, 5th, or 11th graders (the 11th graders were at ceiling with a 97 % correct rate). Perhaps this result also supports that the training has no effect on children (e.g., 4th or 5th grades) who do not have any understanding of the invariance concept. Aside from the age difference, training of the water level task was also found to eliminate pre-existing gender differences (e.g., self-discovery training in Vasta et al. 1996).

8.2.1.3 Transfer

The transfer effect of the water level task is elusive in previous research. First, even though the correct responses of the plumb-line test and the water level task both require the understanding of invariance principles, Vasta et al. (1996) found that the significant improvement from water level training on the water level task did not transfer to Piaget's plumb-line test. This might suggest that although both tasks involve the understanding of invariance principles, they are somehow different. One possibility is that training in water level does not accumulate enough effect to be transferred, or perhaps it is simply the case that water level and plumb line tasks require different cognitive processes. For example, water level might be related to a mental rotation process (e.g., Signorella and Jamison 1978) whereas plumb-line task does not. Secondly, in terms of transfer to academic achievement, there has not been many studies identifying the specific relationship between water level task and STEM achievement. The application of the principle of invariance has been discussed in the process of mathematical problem solving (e.g., Perels et al. 2005) as well as the understanding of multiplication and division (Greer 1994), which might suggest the possibility that training in water level task might improve understanding of these math tasks. In addition, Li et al. (1999) found that SAT scores are highly correlated with the performance in the water level task.

8.2.2 Mental Rotation Test

The very first mental rotation task was developed by Shepard and Metzler (1971), though the most common version people used today was completed by Vandenberg and Kuse (1978), which was adapted from the stimuli from Shepard and Metzler (1971), In the Vandenberg and Kuse's version of the mental rotation task (MRT), 20 three-dimensional mental rotation items were generated with different angles and different lengths of blocks (see Fig. 8.3 for an example item). A redrawn version was also produced by Peters et al. (1995) because the originals of MRT were distorted after many reproductions. The new version consists of 24 items. There are several test characteristics of Vandenberg and Kuse that were similar yet distinct

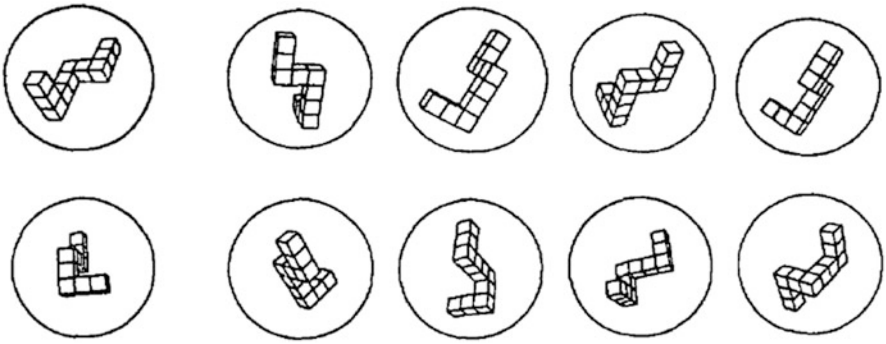

Fig. 8.3 A sample mental rotation task item (Vandenberg and Kuse 1978)

from other spatial tests. First, like the water level task, the item difficulty also is varied by changing the item rotated angles, such that bigger rotated angles result in longer response times (Shepard and Metzler 1971). The most distinct part of MRT is that it has two answers and the test-takers have to answer both targets correctly. According to Vandenberg and Kuse (1978), this is to avoid the possibility of guessing so subjects who only have one correct answer received no credit, although there was no further explanation of how this decreases guessing. By computing a probability of correct rate here, the guessing rate seems to be decreased. For example, using a four foils of multiple choice questions as an instance, the possibility of guessing is decreased from 25 % (1/4) to 17 % (1/2 × 1/3) by asking children to pick two correct answers.

Furthermore, other than the angles of the items changed its difficulty, the types of the distractors (the choices that were not answers) in Vandenberg and Kuse's task are arranged systematically differently. Half of the items have the distractors using the mirror-imaged of rotated targets and half of the items have the distractors using different block configurations from the answer. Because the foils type is also critical for the probability of correctly answering an item, it was hypothesized that that the items have different block configurations as distractors are easier (e.g., Voyer et al. 2004). Voyer and Hou (2006) found the distractors using different block configurations has a high rate of correct responses (Mirrored: 66 %, Structure: 69 %) but the difference between these two different distractors was not significant.

8.2.2.1 Validity and Reliability

Compared to other spatial tests, mental rotation test has been researched broadly in cognitive psychology and neural studies. Previous studies have found that the mental rotation test has proper reliability. For example, the test-retest reliability is 0.83 (Vandenberg and Kuse 1978). For Peters et al. (1995) version, it was found that Cronbach's reliability is 0.87 and split-half reliability is 0.80 (Geiser et al. 2006). Overall, the reliability of MRT is generally good across different versions.

Many studies have suggested that the dimensionality of MRT has a critical influence on participants' performances (Shepard and Metzler 1988). Neural studies also found that 2D and 3D activated different brain areas (Kawamichi et al. 2007; Tagaris et al. 1997). Furthermore, in some studies, mental rotation tasks (such as two dimensional mental rotation task) does not result in male adults advantage in performance (e.g., Rilea et al. 2004). However, fewer studies examined the dimensionality within a single 2D or 3D task. For example, there are some evidences showed that the type of stimulus (hands or blocks) might be influential to the cognitive process recruited of mental rotation tests (Kosslyn et al. 1998), and some showed different result with slight changes on stimulus such as different number of the cubes being used in the blocks (e.g., Bryden et al. 1990). However, when considering the cognitive processes involved in the mental rotation task, multidimensional processing has appeared when the processing of specific items were examined. Studies have found that different cognitive processes were occurred within different items of the 3D task (e.g., Voyer and Hou 2006). Neural researchers have suggested mental rotation involves both analog spatial representation and motor processes (Zacks 2008). All these suggests the potential existence of multidimensionality in mental rotation tasks further research is need to validate its precise structure.

Mental rotation task is considered as an intrinsic dynamic type of spatial task in Uttal et al.'s paper (2013). It is defined as "Piecing together objects into more complex configuration, visualizing and transforming objects" (page 4). Other tasks in the intrinsic dynamic category, such as paper folding and block design, along with mental rotation, seem to be categorized differently by Linn and Petersen (1985). For example, mental rotation is in mental rotation section while paper folding is in spatial visualization in Linn and Petersen (1985). Some evidence suggested that paper folding and mental rotation might be in the same category. For example, Harris et al. (2013) compared and contrasted findings from psychometric and neural studies between mental rotation and paper folding tasks and suggested these two tasks are very similar in many aspects. In Kozhevnikov and Hegarty's (2001) study, they also found that within a confirmatory factor analysis model both tasks loaded significantly on the same latent factor, suggesting at least a significant part of both tasks are loaded on a single dimension.

8.2.2.2 Training

Training on mental rotation task has shown successful results across different populations. Specifically, mental rotation training is effective both on children (De Lisi and Wolford 2002; Ehrlich et al. 2006) and adults (McGee 1978; Terlecki et al. 2008), and also improved the gender difference in favoring males before the training (Neubauer et al. 2010). Furthermore, studies also have shown that improvement of mental rotation scores can be linked to neural efficiency (decreased brain activation; Neubauer et al. 2010). Both virtual and paper versions of mental rotation trainings are shown to be effective as well. For example, a study found that a video training can be effective (De Lisi and Wolford 2002), while another study showed that both video and practice training were effective on improving mental rotation scores (Terlecki et al. 2008).

8.2.2.3 Transfer

Interestingly, not only mental rotation performance can be improved through practicing it, several studies have shown that its transfer effect is quite effective and can be generalized to other similar tasks (Wright et al. 2008; Stransky et al. 2010) or spatial visualization task (Sanz de Acedo Lizarraga and Garcia Ganuza 2003). Furthermore, among these studies, it was found that hands-on activities can be helpful for increasing mental rotation ability (e.g., Jansen et al. 2009; Wiedenbauer and Jansen-Osmann 2008). For example, Wiedenbauer et al. (2008) found that their manual training can lead to improvement on untrained stimulus that usually did not improve through the practice type of training. Perhaps this is linked to the possibility that the strategies used to mental rotation might be connected to motor processes (Wexler et al. 1998). Mental rotation has showed significant relations to STEM achievement (Bruce and Hawes 2015; Stransky et al. 2010; Reuhkala 2001), but the transfer effect to STEM fields is mixed., It was demonstrated that the effect can transfer to improvement on math skills such as missing terms problems (Cheng and Mix 2014) or college introductory physics grades (Miller and Halpern 2013), though some other studies have found no effect (Hawes et al. 2015).

8.2.3 Visual Spatial Working Memory (VSWM)

As one of the subsystems of working memory structure, VSWM has been studied more extensively compared to other spatial abilities. Although an unidimensional view of VSWM defines it as a psychological construct that temporarily holds visual and spatial information (Baddeley 1986, 2000; Quinn 2008; Reuhkala 2001), different subsets of VSWM (e.g., static VSWM and dynamic VSWM) have been used across different studies. (e.g., Corsi 1972; Della Sala et al. 1999). Among these different VSWM tasks, there are several ways to categorize them. For example, one way is to separate these as static VSWM and dynamic VSWM constructs (or they can also be considered as simultaneous and successive VSWM tasks). Between these two categories, one of the representative VSWM tasks, which is developed from the static VSWM construct, is the visual pattern test (Della Sala et al. 1999, see Fig. 8.4 for an example item). The visual pattern test (VPT) is administered by briefly showing a matrix with patterns of blank cells and filled cells (for 3–5 s) and then asking the subjects to indicate what they remember. The score is estimated by counting the number of cells in the given most complex matrix that children can correctly mark (the score range can be from 0 to 15). A different way of score calcualtion is using sum score. See an example in Kaufman ABC test: Spatial Working Memory test; Kaufman and Kaufman 1983) Another representative VSWM task

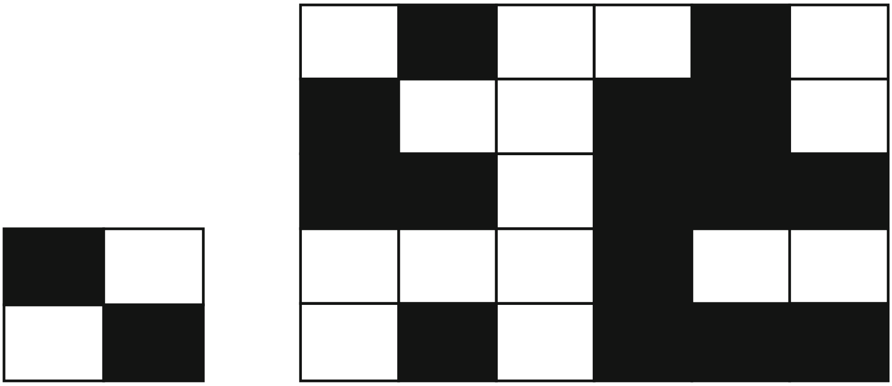

Fig. 8.4 A sample item from visual pattern test (Della Sala et al. 1999)

that is developed from the dynamic VSWM construct is the Corsi block task (Corsi 1972). The Corsi block test measures whether children can successfully reproduce the sequential order that the experimenter tapped on the three dimension blocks.

8.2.3.1 Validity and Reliability

The reliability estimate of VSWM is not always included in studies, though a few studies have provided some of them. For example, for the VPT, the reliability of test-retest is 0.75 on both forms A and B among 50 subjects aged 20–81 years (Della Sala et al. 1999). For the Corsi block test, odd-even reliability (range from 0.70 to ~0.79) is with age 11–16 year old adolescents (Orsini 1994). Friedman et al. (2006) used a spatial two-back task which indicated internal consistency of reliability with a Cronbach's alpha of 0.91. Overall, these reliabilities seem to be adequate among VSWM tests with certain ages, though it is unknown whether similar reliabilities would be found in other populations.

The validity of VSWM construct has been established by showing that a single, independent factor of VSWM can be isolated through confirmatory factor analysis when other working memory tasks were included in the same model (Kane et al. 2004; Miyake et al. 2001). For example, Kane et al. (2004) were able to separate VSWM from general working memory, and the model they proposed also confirmed that one VSWM latent factor can be extracted with three VSWM tasks (rotation span, symmetry span, and navigation span). However, although VSWM is an independent psychological construct, the question remains as to whether multidimensions exist within VSWM.

As mentioned earlier, many studies have developed different VSWM tasks, but they might measure slightly different construct. For example, both VPT and Corsi block tasks require people to remember a brief picture and recall the location of objects presented in the examples. However, one difference is in the procedure: the stimuli of VPT are presented in a simultaneous way and the Corsi block task was presented in a sequential way. Recent neural evidence has shown that these two types of tasks appear to have different patterns of activation in the brain (Darling et al. 2006). There is also behavioral evidence to show that when having people performed dual tasks, visual interference will decrease the performance of VPT task but not on the Corsi task, and spatial interference will decrease the performance of the Corsi task but not on VPT task, which also implies two separate cognitive processes (Della Sala et al. 1999). Therefore, the cognitive processes of static VSWM and dynamic VSWM are suggested to be somehow independent through factor analysis (Vecchi et al. 1995), meaning these processes can be considered two separate dimensions within the concept of VSWM.

There are also studies that examine VSWM more closely across many different VSWM tasks and find that there are more than two sub-dimensions. For example, Mammarella et al. (2008) examined the components of VSWM using confirmatory factor analysis on third and fourth graders. They found that four dimensions coexist within VSWM: sequential-spatial, simultaneous-spatial, visual, and visuospatial active factors. In their study, the division of dimensionality of VSWM seemed to be task specific, such that each factor could be extracted from two or three similar VSWM tasks, suggesting that only several similar tasks shared a common dimension.

Furthermore, in each VSWM task, perhaps the cognitive processes can be hypothesized to reveal more than one dimension. The hypothesis, theorized from Kosslyn's (1983) classical work on mental images, speaks of two types of spatial processing within image generations. One is with a categorical spatial relationship, and the other is with a coordinating spatial relationship. A categorical spatial relationship is the categorizing processing by which people remember the general structure of stimuli, and a coordinating spatial relationship is the location recoding process by which people remember where stimuli are located. This suggests that people understand spatial relationships through two different systems, according to their structure and the exact location of the objects under scrutiny. Many studies in neural imagining have also shown hemispheric specialization for categorical and coordinate relationships: categorical memory has more activation in the left hemisphere and coordinate memory has more activation in the right hemisphere, also suggesting that these are two separate memory systems (e.g., Trojano et al. 2002; van der Ham et al. 2009).

Similarly, Vecchi et al. (1995) found that the amount of information and the structure (the location of the objects) of the VSWM stimuli are two important factors that influence the storage capacity of VSWM. Concluding from these studies, how people remember these changes in structure and how people remember the number of stimuli may be allocated to different dimensions. This multidimensional view of VSWM is not only supported by researchers in behavioral studies (e.g., Logie and Van Der Meulen 2009), but also from neural imagining studies. For example, a recent neural study has demonstrated that there might be two separate cognitive subsystems operating within VSWM (Darling et al. 2006). Overall, these findings imply the possibility that multiple dimensions may exist within in one type of VSWM task.

Few studies, however, have investigated how or whether these dimensions in one type of VSWM (e.g., static VSWM, the basic form of VSWM) can be separated. Based on the separate activations found braining imagining studies, it can be speculated that there may be at least two dimensions in one VSWM task, depending on the location and appearance of the stimuli in the task. However, other researchers have also suggested that the separation between categorical spatial relation and coordinate spatial relation might not be as discrete, as they found that these two tasks show similar activations in their experiments (Martin et al. 2008).

8.2.3.2 Training

As described above, training in VSWM is often included in composite working memory-training programs. Such a composite training program shows improvements on VSWM across different programs, both immediately and in follow ups, but several studies showed a small effect size for immediate improvement (see a meta-analysis in Melby-Lervag and Hulme 2013). Neural imagining studies using VSWM tasks also have demonstrated that the improvement of VSWM performance can be associated with the brain activity in the middle frontal gyrus and superior and inferior parietal cortices. (e.g., Olesen et al. 2004), which suggests the possible connection between VSWM training and brain plasticity.

8.2.3.3 Transfer

Using VSWM training to improve other spatial abilities or academic achievement (such as in mathematics) is prevalent in previous studies. However, such effects have been mixed (Chase and Ericsson 1981; Holmes et al. 2009; Jaeggi et al. 2011; Kyttälä and Kanerva 2014; St Clair-Thompson et al. 2010; Van der Molen et al. 2010). VSWM is found to be trainable even when other cognitive abilities were less effective (e.g., Owen et al. 2010). Even so, the generalizability of VSWM training is inconsistent across measures. For example, in an experiment reported by St Clair-Thompson et al. (2010), children ages 5–8 were trained in composite working memory techniques, including visual image rehearsal strategies, for 6–8 weeks. The training did not improve their performance in the block recall task (a dynamic VSWM that is similar to the Corsi block task) or the digit recall task, but it did improve mental calculation performance. This perhaps suggests that training VSWM to improve math performance is possible, even when the training does not improve other types of VSWM tasks. However, the study itself had a composite training and it was difficult to determine where this effect came from. Furthermore, this specific relationship between VSWM and math might be bidirectional, such that math can improve VSWM as well. For example, Lee et al. (2007) discovered that a year's math training (given once a week) in the use of the mental math abacus (a Chinese math calculation tool) improved the performance of 12-year-old children in simple spatial span tasks, but not in complex spatial span tasks (a task that involves both an equation and a presentation of dots in squares). Overall, training one type of VSWM task does not necessarily improve other types of VSWM tasks, but it might improve some types of math tasks; additionally, training specific math tasks can improve specific types of VSWM. These studies show that VSWM and math have some cross-generalizability, but it is task-specific.

8.2.4 Map Reading

Compared to other spatial tasks, only a handful of tasks have been developed to assess children's potential on map understanding, and they were developed specifically for certain grades. For example, Presson's (1982) map task was designed to test kindergarten and second grade students. Kastens and Liben (2007) adapted Liben and Downs' (1989) flag-sticker field-based map skills test to create a map-reading task for fourth graders. However, across the tasks, the instructions were similar in terms of how subjects were asked to find the location of the targets (see Fig. 8.5). For example, in Kastens and Liben's (2007) map reading task, children were asked to place flags on a map when they were shown an actual flag in a real field area.

The difficulty of the items usually varied by the rotation of the targets (e.g., Presson (1982) or by varying the locations of unique or repeated map symbols, which was recommended by previous research because locations near unique locations might be easier (Kastens and Liben 2007). The scoring scheme is sometimes twofold. For example, in Kastens and Liben's (2007) study, one score was generated from measuring the linear distance from the target to the child's placement (so a longer distance means a higher error rate), and another estimate was generated from categorizing the children's errors to identify children's level of understanding of map concepts.

8.2.4.1 Validity and Reliability

Few studies have examined the map task through the traditional test construction procedure to identify the psychometric properties of the task. While in the previous studies, the development of map understanding has three stages: symbol recognition, metric understanding, and projective view (Liben and Downs 1989), some map reading tasks have identified the development of concept through children's error types (e.g., Kastens and Liben 2007).

Several studies have further differentiated map reading into several different cognitive processes and studied their neural similarity and differences (Shelton and Gabrieli 2002; Shelton and Pippitt 2007; Yamamoto and DeGirolamo 2012). For example, Shelton and Gabrieli (2002) found that the route encoding task and the map overhead reading task recruited similar neural activations on the bilateral fusiform, inferior temporal gyri, and posterior superior parietal cortex. Further, although

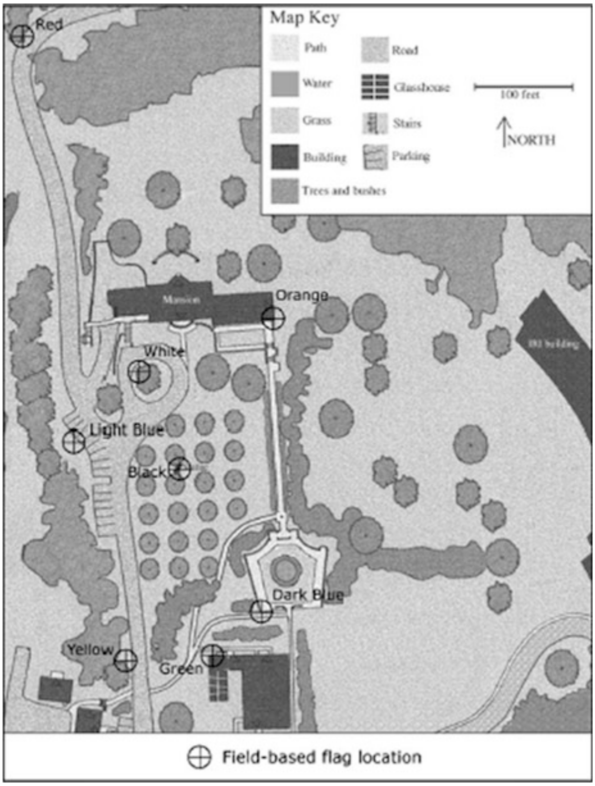

Fig. 8.5 The *black* and *white* version of map reading test (Adapted from Kastens and Liben 2007)

the map overhead reading task recruited greater activation, the route encoding task had a larger area of activation. Specifically, route coding recruited the bilateral medial temporal lobe, postcentral gyrus, right posterior cingulate, and left medial frontal gyrus. Shelton and Gabrieli (2002) considered this as supportive evidence of a hierarchical relationship between route learning and map overhead reading in child development (e.g., Herman and Siegel 1978), which might also suggest multidimensionality within map reading. In terms of spatial categories, while Uttal et al. (2013) categorized map reading task as dynamic and extrinsic, Linn and Petersen (1985) did not specify where map reading tasks should belong.

8.2.4.2 Training

Several studies also further explored the role of instructions in improving children's map reading ability (e.g., Kastens and Liben 2007). For example, Kastens and Liben (2007) compared and contrasted two experimental conditions (ask children to give self explanation on answers vs. no explanation) on a map reading task in fourth graders. Using the distance score, the researchers found that the self-explanation group had significantly less error scores compared to the no explanation group. The authors suggested that perhaps the self-explanation provided a strategy for children to identify and notice the clues in the environment and therefore improved their performances. However, the self explanation group also spent longer time to complete the task (time interval for the activity: 45 mins vs 15–20 mins); perhaps spending enough time on each question can help students to rethink about their answers better and therefore perform better. Overall, the self-explanation group committed fewer errors. The researchers used a distance score procedure, which might be more sensitive, compared to dichotomous responses (0 or 1), and therefore might produce higher sensitivity on identifying children's responses.

Another somewhat different approach used in map reading improvement is decreasing the complexity of map reading tasks by improving subjects' cognitive processing in some components of the task. Map reading contains a lot of different aspects of information processing; therefore, eliminating one aspect of cognitive load might potentially improve the performance is the rationale behind this approach. For example, Fisk and Eboch (1989) adopted automatic processing theory to develop a training protocol. The result suggested that automatic training did improve map reading task performance. However, because the task procedure was only asking the subjects to identify the legend on the maps, which requires symbols reading, there was no item measuring the concepts of spatial orientation or scaling that is often shown in other map reading tasks. Nevertheless, this study demonstrated that training on one component could facilitate learning a multi-components map reading task.

8.2.4.3 Transfer

Few tasks have examined the transfer effect of map reading task (Griffin 1995). Among these, Griffin (1995) examined two approaches (situated learning and traditional learning) in map skills of fourth graders. In the situated group, the students were brought to the environment pictured in their maps while the traditional group received instructions from overhead projectors and writing exercises of map reading skills. The results showed that the situation group performed better than traditional group on the target map performance task but not on the transfer task (which was a novel map task that required the same map skills). The author argued that cognitive skills are context-bound and hard to transfer. A few studies have looked at if other spatial related training might have effects on map reading skills. Klahr and Carver (1988) found that improvement of debugging computer programming skills correlated with a map route following task with a age mixed group including third grade through sixth grade students.

8.3 The Improvment of Spatial Ability.

8.3.1 *What is Improved in Spatial Training?*

Form the discussion above, one can find that the attempts to improve the performance of spatial abilities through spatial training have gained many successes (also see a meta analysis in Uttal et al. 2013; Wright et al. 2008). It was evidenced that spatial ability is quite sensitive for training effects, and perhaps part of this effect is related to the fact that spatial ability is related to spatial experience (Baenninger and Newcombe 1989). Therefore spatial trainings that simply repeated the procedures to increase spatial experiences have been shown improvement of performances of spatial tasks (e.g., Ehrlich et al. 2006; Cheng and Mix 2014).

Spatial training effects can also transfer across different spatial abilities. Uttal et al. (2013) meta-analyzed previous spatial studies along with the two by two typology categorization that they have developed to calculate the effect size of transfer effects within each category (whether tasks belong to the same category can transfer) and across category (whether tasks belong to different spatial categories can transfer). The results showed that the effect sizes (using Hedges's g) within category ($g=0.51$) and between categories ($g=0.55$) are quite similar. This might suggest that training in any spatial task could possibly improve any other spatial tasks even though they are in different categories here. Although this result seems to imply that spatial ability is a single construct, the possibility that spatial ability might still be multidimensional remains. It is possible that different spatial cognitive processes were merged in different spatial tasks, but all spatial tasks might share similar ingredients of cognitive components with different combinations of processing. Training certain components that were largely shared by several spatial tasks will improve these tasks but not otherwise. For example, all spatial tasks require visual spatial working memory (VSWM) to remember the characteristics of stimuli. Perhaps training VSWM can enhance most of the spatial abilities tasks. Another example is the rotation process. Recall that rotation processes might be recruited during several spatial tasks such as the water level task (e.g., Kalichman 1988), the mental rotation task (Vandenberg and Kuse 1978), and the map-reading task (Presson 1982). It is possible that training rotation processes will improve these spatial tasks more than other spatial tasks. Though most spatial studies showed improvement on spatial abilities, some studies showed less improvement compared to others. Although this outcome has been discussed broadly based on the design of the training such as whether it was within or between subject, or the training methods used such as video, course, or spatial task (for a review, see Uttal et al. 2013), less has been discussed on how these training effects were identified through spatial outcome measures. However, a successful training effect is not only dependent on the effective training design, it is also dependent on the sensitivity of the outcome measures.

The performances of previous spatial tasks were estimated from two main approaches: (1) Using the sum scores from dichotomous items (e.g., VSWM or mental rotation task); (2) Using the degree of error or distance scores (map reading or water level task). Both approaches were able to identify the improved ability from previous studies as they all successfully detected the improvement of spatial performances. However, estimation of degree of error or distance scores might have more advantage compared to a dichotomous item sum score because scores using dichotomous responses have constrained the judgment of participants' performances to a certain degree, which might lose some sensitivity compared to error scores in detecting how far off a participant is from the true target, which might be closer to participants' underlying true abilities. Although all spatial training seems to be effective, this difference might be important for detecting further transfer effects. Furthermore, the approach of using the sum scores to serve as an indication of training gain might have some potential issues as it weights each item equally. What could happen, specifically, is that students answered difficult items correctly might not be weighted more despite of their higher abilities. One way to avoid this problem might be using an extensive range of item difficulty when developing test items.

Secondly, the common issue with using sum scores or sum error scores from single spatial task is that such a score comes with the assumption of measuring the construct perfectly. Therefore the measurement error is to be neglected. Several studies have adapted the latent variable approach to identify the growth of improvement (Embretson 1991; Noack et al. 2014). Such an approach utilizes the latent variable modeling on several variables (that belong to the same constructs) to identify the change of the latent mean and also account for measurement errors. Another measurement issue from previous spatial studies was that certain constructs have to be measured with the format of multiple choices because the attribute might not be able to be measured as an absolute error (or distance) score from the underlying ability (e.g., choose the correct block configuration of the mental rotation task). However, the quality of multiple choice items is also related to the selection of their distractors. The choices of distractors might certainly change the discriminating degree of the items (Haladyna et al. 2002).

Other than the traditional psychometric methods, recent development of neural imaging research has introduced a new perspective to measure the effectiveness of spatial related training (some part of these cognitive training programs). People have used the structures of neural mechanisms to identify the brain areas that are linked to spatial related cognitive trainings and positive effects were found in previous studies. For example, McNab et al. (2009) found that a cognitive training involving spatial memory components is associated with changes in both prefrontal and parietal D1 binding potential, which has been identified to be associated with improved working memory capacity. Raz et al. (2013) found that less brain shrinkage (brain shrinkage happen when we get older) of the cerebellum is associated with cognitive training (spatial working memory involved). Although the results seem to be promising, the above studies involved multiple components (verbal and spatial) in the training process. It is therefore difficult to identify the part of the training associated with this change in brain.

A few studies have further explored the effect from trainings that only have spatial training processes. These studies have also identified positive effects in the brain after the training. For example, in terms of orientation (one type of spatial processing), Wenger et al. (2012) discovered that after spatial navigation training, cortical thickening in left precuneus and paracentral lobule was found with their 20–30 year old participants. Other than identifying whether the positive effect is associated with training, neural approaches also help to identify which different strategies might be involved in spatial tasks. For example, Kosslyn et al. (2001) found that when subjects were asked to imagine rotation with their own hands, this type of imagination activates the motor areas (such as primary motor cortex), whereas the subjects who were asked to imagine the rotation from external sources did not show the same activation. Some studies further examined the relations between item difficulties and brain activity. For example, Ando et al. (2009) found that compared to 10 objects in one stimulus, 30 objects in one stimulus has extended the brain activation in the frontal lobe. These studies might suggest different paths of strategies might be recruited with different numbers of objects and each of these is associated with different degree of brain connectivity.

8.3.2 The g *Factor*

As mentioned in the first section of the chapter, spatial ability has been found to have significant relations with STEM achievement. The directionality of these relations is unclear. However, the relation between STEM and spatial abilities might be discussed more broadly under the relation between academic achievement and cognitive abilities. Many studies have found significant relationships between academic achievement and cognitive abilities (Best et al. 2011; Deary et al. 2007; Gustafsson and Balke 1993; Passolunghi and Lanfranchi 2012; Rohde and Thompson 2007; Spinath et al. 2006). The range of correlations is wide, from 0.40 to 0.90, and at the extreme end, a correlation of 0.90 suggests 80 % of the variance in each is shared. This relation might be because they are both influenced by the same general intelligence factor (*g*). Lynn and Meisenberg (2010) have tested this hypothesis using factor analysis. What they found is that after correcting for unreliability (using the attenuation procedure from Ferguson 1971), that the correlation between the general factor extracted from cognitive tests and the general factor extracted from scores on achievement tests over the course of one school year is 1.0, suggesting one common general ability influences both academic achievements and cognitive abilities. Therefore, scores for an academic achievement (e.g., reading, math, or science) can be viewed as a sub-dimensions under the broader construct of general ability. Follow this logic, it is reasonable to hypothesize the significant relations between STEM achievement and spatial abilities could be because they share a general factor.

8.3.3 Can Spatial Training Improve STEM Achievement?

Because these two constructs might share a general factor, the possibility that training cognitive abilities, specifically spatial abilities, might further improve STEM has drawn attention. For example, previous researchers have argued, perhaps spatial ability is critical for early learning stage of new STEM concept (Uttal and Cohen 2012).

The question of whether spatial training improves STEM achievement actually goes beyond the question itself and can be extended to several levels of inquiries. The first inquiry is whether this predictive relation could also be considered in a reverse direction. Specifically, whether STEM training improves spatial ability or whether such an effect can be reciprocal during the developmental span (Farmer et al. 2013). For example, perhaps learning mathematics itself is a spatial training process and when a person is better at mathematics they are also improved their spatial abilities. The second inquiry, which is often brought by STEM educators, is what the benefits are of doing spatial training when training with STEM contents can directly improve STEM achievements. Indeed, STEM training improves STEM achievement, but these trainings are also context-bound. For example, in math education, Campbell et al. (2006) found training people in addition problems did not improve their performances on subtraction problems. Rickard et al. (1994) also found no transfer of skills between similar division problems (the participants practiced 56/7 = 8 and were tested on 56/8 = 7), suggesting the training effect is specific. Although it is not guaranteed that spatial training will help people transfer their knowledge to mathematics problems, spatial training has showed efficient on transfer effect to other spatial tasks, implying the flexibility of spatial thinking. For example, if we consider the spatial processing from the above mathematics problems, one possible outcome is that training underlying spatial processes might help people to be able to connect and apply the mathematics concepts more flexibly.

Whereas spatial training seems to be promising as a powerful tool for STEM achievement theoretically, spatial training studies did not have many successful cases in improving STEM achievement practically. As many studies have demonstrated the significant relations between spatial ability and STEM (Best et al. 2011; Deary et al. 2007; Gustafsson and Balke 1993; Passolunghi and Lanfranchi 2012; Rohde and Thompson 2007; Spinath et al. 2006), these mixed results from studies cast doubts on the transfer effect of spatial training to STEM. First, there are simply not enough spatial studies to attempt to improve achievement on STEM field to be judged whether this approach is effective. However, here is what is known from current studies—previous spatially related working training programs have showed some improvements (e.g., St Clair-Thompson et al. 2010), when meta-analysis tried to identify the effect of verbal and visual-spatial training, spatial memory training has limited but a convincing effect size (Melby-Lervåg and Hulme 2013). Nevertheless, training and learning a composite cognitive training program might be such a complex process and it would probably lead to learning less about each specific aspect of the task. As a result, individuals may demonstrate less mastery on the trained tasks, let alone improved overall ability. This process is similar to mastering a sport such as basketball. Athletes learn how to move the ball, how to pass a ball, and how to score a basket. The mastery of each specific process is needed to ultimately master basketball as a whole. This step-by-step learning process is likely similar in the brain. Learning one specific cognitive process at a time may help to encourage the thought process needed for a task or may even transfer to other tasks that have applied these specific processes. This type of training might then provide a better outcome than the learning of many different processes at one time.

Secondly, in order for transfer to happen, the underlying processes of transfer mechanism need to be identified. Previously, studies had posited some potential mechanisms behind a successful transfer. Perhaps some processes shared between the trained tasks and improved measures underlie the above generalizable examples. An example is Wallace and Hofelich's (1992) study. In the study they had some participants complete training in mental rotation who were then tested in a geometric analogies task. They had the other group of participants complete training in a geometric analogies task and then tested them in a mental rotation task. Specifically, in the geometric analogies task, the participants were asked to view several shapes, all of which could be combined as an object that still involved one missing piece; they were then asked to also identify which of five options was the missing piece. In the mental rotation task, the participants were asked to identify whether the orientation of objects was standard or mirrored. They found that training in either task improved the performance in both, even though these two tasks did not share similar contexts. The possible mechanism, as explained by Wallace and Hofelich (1992), is Process Theory (Kosslyn 1983), which stresses the importance of similar cognitive processes on task transfer. The argument for this effect is that when two tasks emphasize the same processes, training in either of them should be able to produce a generalized effect on the other. Additionally, this study demonstrated that the improvement between cognitive tasks could be bidirectional.

This phenomenon is not limited to mature adults. Kloo and Perner (2003), for example, found that training children ages 3–4 in an executive control task and a theory of mind task led to improvement on both. Executive control was trained and assessed with a Dimensional Change Card Sorting task (DCCS; Frye et al. 1995), and the theory of mind test was trained for and assessed using false-belief tasks. The improvement of both suggests that the generalization of training effects is possible with children. Kloo and Perner (2003) made a similar argument as Wallace and Hofelic's (1992), suggesting that there may be a specific underlying common factor in these two improved tasks. While these transfer examples showed that transfer effect was possible when the shared processing is defined, there is currently not enough evidence to define the shared processes between STEM and spatial ability, As a result, the question remains as to what is the underlying structure between spatial ability and STEM achievement can be identified and trained to make that transfer happen?

8.3.4 The Cognitive Processes Underlying Spatial Ability and STEM

Identify the underlying cognitive processes among spatial ability and STEM achievement has be developed from several approaches. From the psychometric approach, researchers have been using measurement models to identify whether the same construct is measured across different populations. For example, measurement invariance models were applied and identify the measurement and structural invariance of the construct (e.g., Byrne et al. 1989; van de Schoot et al. 2012). Furthermore, in order to identify the items have discriminating powers on participants' abilities, to estimate the participant's underlying abilities or attribute more accurately, item responses models (Embretson and Reise 2000; Reckase 1997) or diagnostic classification models (e.g., Birenbaum and Tatsuoka 1993) also has been proven to be useful.

Researchers also have worked from the perspective of cognitive science to understand the underlying cognitive process. For example, researchers discovered such a process by doing dual tasks experiments. Specifically, the participants were asked to do one task when another interference task was on the background. By doing so, researchers gained clues about whether these two tasks share the same functional processes in the human brain (e.g., Pashler 1994; McKenzie et al. 2003). Furthermore, recent developments in brain imaging research have extended this approach by determining whether two tasks activate similar brain areas and are therefore using the same processes (e.g., Hubbard et al. 2005) or connect the specific function of the memory tasks with the specific brain areas (see studies in meta analysis of Wager and Smith 2003).

These two approaches have provided many insights on the underlying cognitive processes. However, each of them has its disadvantage. While modeling human responses from a statistical perspective has providing many possible inferences, the results might be rested on relatively better models compared to other models. On the other hands, although neural studies have helped researchers to identify the cognitive processes to the level of item level, building a reliable item analysis from neural studies requires a significant sample size, which might be a reason that different results often come out with different studies. A possible way to solve this problem might be using a large sample with the hypothesized models that were generated from a meta-analysis of previous neural studies. Connecting the item response with neural network might be a new approach although revious studies have demonstrated item diagnostic methods within artificial neural networks (Lamb et al. 2014) While item response models are applied across cognitive psychology studies, few applicated have been made in brain imaging studies. For example, recent studies have used item response models to understand learning (Embretson 1991) and growth change (McArdle et al. 2009), as well as to explore the structure of a cognitive ability such as phonological awareness (Schatschneider et al. 1999). An extension of IRT models, multidimensional item response models (Reckase 2009), was also used to identify the dimensionality of a ninth grade math test (Ackerman et al.

2003) and a test for English language learners (Reckase and Xu 2015). Item response models have been applied extensively in the construction of achievement tests and might be promising to connect with the ample research from neural studies to explore the structure of spatial ability and STEM achievement.

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Chapter 9
A Spatial-Semiotic Framework in the Context of Information and Communication Technologies (ICTs)

Melih Turgut

9.1 Introduction

Let me begin this chapter with a personal anecdote. When I was in primary school, I was always interested in the notion of *space*. I tried to imagine it through my own experiences from textbooks, models, classroom discussions and television; a dark, gas-free environment, with shining stars, a visible earth, other planets, and also positions and movements of the planets and the sun. Now, looking back at my imaginative efforts, I am able to see my struggle created an *amalgam* of existing *mental images* (i.e., *mental pictures*) taken as input from previous processes and from nested figures to construct *dynamic images* of space. How did I create such mental and dynamic images, and what kind of processes was I involved in? It is clear that I was navigating in the solar system myself, and manipulating the objects in my mind and imagining them from different viewpoints, but, at the same time, I was unconsciously moving my body, in particular my head and my hands. In other words, I was using a specific ability to construct new mental and dynamic images, my *spatial ability*, but interestingly, through my body's specific movements.

Referring to my own thinking processes described above, it was only one experience that remember; what about for our entire life? As individuals living in three-dimensional space, we are always using our spatial ability in daily life. For instance, not only limited to learning 2D or 3D geometry, but also to finding locations through our mental map, while placing self-assembly furniture around the house or while playing computer games. The last example is important in emphasizing spatial ability's capacity to enable a user to take mental images as input and to produce dynamic images quickly. You can think of such a game player as an individual looking at a flat monitor, which is providing the user an immediate (sequence of) *transformation*

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that can be assumed as specific transformations from space $\mathbf{R}^2$ to $\mathbf{R}^3$ by showing the user 3D objects throughout. However, I would like to differentiate the playing a game process from watching a movie, and yet their construction source is dependent on the user's movements or acts. I identify the construction of dynamic images through ICT into two areas: *dependent* or *independent* from the user. Playing a computer game, including the production of dynamic images is dependent on the user acts. However, at the same time, the user's body movements may also appear in the process. What is the process do users follow while they pursue a similar dependent process whilst thinking spatially? What would happen if the subjects use 3D modeling software? What kinds of *signs* emerge in this process? Combining these with the earlier questions, in this chapter, I will try to elaborate a framework describing subjects' spatial thinking (i.e., visualization) processes in a multimodal perspective, while they are using 3D modeling software in the exploration of spatial ability tasks. I will try to analyze and discuss such a framework in terms of two case studies, mirroring a multimodal paradigm, in particular, with a *semiotic lens* of different source of *signs*, based not only on discourse, but also on extra-linguistic acts, such as *gestures*, *sketches*, *graphs* and so on. I will consider the Action, Production and Communication space framework (Arzarello 2008; Arzarello et al. 2009; Arzarello and Sabena 2014) to address a piece of recent extensive research data, where partial results are presented through the *instrumental approach* (Turgut and Uygan 2015).

This chapter is distinguished into the introduction and five main sections. In the second section, I try to review, summarize and describe certain concepts and processes; mental and dynamic images, visualization, and spatial thinking, specifically in the context of 3D modeling software. In the third section, I provide the reader with the notion of semiotics in the sense of C.S. Peirce and its relation to mathematics education, with an embodied cognition perspective. In the fourth section, I try to elaborate a spatial-semiotic framework for spatial thinking through the theoretical underpinnings from previous sections. In the fifth section, I approach two case studies to discuss the proposed framework using a multimodal paradigm, completing the chapter with a conclusion. Finally, the sixth section covers a discussion of the results and limitations of the study.

9.2 Mental and Dynamic Images, Process of Visualization and Spatial Thinking

Generally speaking, spatial ability can be defined as a combination of different (sometimes, *nested*) sub-skills creating various visual-spatial images and generating information, such as, visualizing 2D or 3D stimuli, rotating them mentally, and visualizing them from different viewpoints (Hegarty and Waller 2004; Linn and Petersen 1985; McGee 1979; Olkun 2003). Although there are several definitions of sub-skills in the related literature (Linn and Petersen 1985; Lohman 1996; Maier

1998), as a general reference, spatial ability can be categorized into two areas (McGee 1979); *spatial visualization* that refers to several sub-skills, such as projection skills from 2D to 3D (or vice versa), imagining and manipulating the objects mentally, which includes rotating objects mentally, and *spatial orientation* that refers to imagining objects from different viewpoints.

Certain questions relating to the core aim in this chapter arise. How do those specific images, belonging to spatial visualization or spatial orientation, occur in our minds and why learning about the spatial thinking process is really important? As Dreyfus (1995) emphasizes, a researcher studying the learning of mathematics within a psychological perspective has to be aware of the *internal representations* of learners, as well as associated *external representations*, to possibly understand the learners' interpretations of figures, diagrams and suchlike. This is because we are interested in how internal representations are created, and how they affect an individual's creation of *visual-spatial images*, which also affect his/her mathematical reasoning while solving context-specific spatial tasks. However, inductively, the creation of visual-spatial images may be in relation to an individual's phenomenological experiences, i.e., their interaction with associated *objects* and their *interpretants* as 'internal spatial abilities', mediated by *signs*, which may be discussed by the seminal *semiotic triad* of C.S. Peirce (Buchler 2015; Yeh and Nason 2004, p. 4). I will return to this semiotic perspective in later sections to interpret students' spatial thinking processes, in particular, while they are using 3D modeling software.

Before outlining spatial framework of this chapter, I will look at certain specific terms that researchers use while elaborating the aforementioned internal representations in the spatial reasoning process (in the context of learning geometry). These include *mental images*, *mental pictures*, *spatial images*, *visual images*, *visual imagery*, and *dynamic images* or *dynamic imagery*. In addition, there are also references to the spatial reasoning process; *visualization*, *visual thinking*, and *spatial thinking*. I agree with Gutiérrez (1996), who notes that researchers express (i.e., through visualization or spatial thinking) such terms interchangeably, but at the time synonymously.

Hauptman (2010, p. 124) proposes that a *spatial image* 'is the end product of a mental process that uses various aspects of a concrete object (or objects) to create a picture of that object in our mind'. However, this definition apparently has a general viewpoint and includes several kinds of processes. A complete classification for such images is provided by Presmeg (1986, 2006) from the point of view of learning mathematics (as a general reference, not only belonging to the learning of geometry) in terms of qualitative analyses that she conducted. She defines *visual image*s as 'mental constructs depicting visual or spatial information' (Presmeg 2006, p. 207), and describes how, in the *visualization* process (i.e., construction and/or manipulation of visual images), an individual can use and/or need one or more of the following kinds of imageries (Presmeg 1986, pp. 43–44):

- *concrete*, *pictorial imagery*, which is related to real-life contexts, already created 'pictures in the mind'.

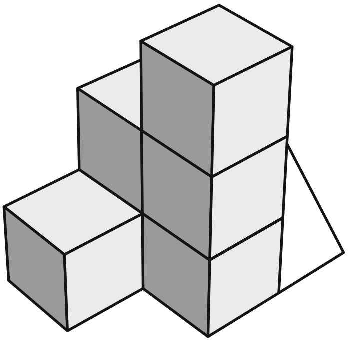
- *pattern imagery*, which refers to visual mathematics-ready patterns in the mind, for instance, 30-60-90 triangle and associated lengths.
- *memory images of formulae*, remembering and/or seeing formulae in the mind.
- *kinaesthetic imagery*, muscular and physical acts and movements attached to the process of describing figures, objects or mathematics.
- *dynamic imagery*, which refers to the creation and transformation of dynamic mental images in the mind in the process of visualization.

After a careful analysis and elaboration of definitions and theoretical constructs on spatial ability, mental-visual-spatial images in psychology and mathematics education literature, Gutiérrez (1996) expresses that, 'a mental image is any kind of cognitive representation of a mathematical concept or property by means of visual or spatial elements'. He also considers *visualization* as a general reference to spatial reasoning or spatial thinking, saying that it is, 'a kind of reasoning activity based on the use of visual or spatial elements, mental or physical, performed to solve problems' (p. 9). Referring to the same term, Bishop (1983) proposes two kinds of spatial-mathematical *abilities* in an individual's process of *visualization*; the ability to *interpret figural information* (IFI) and the ability to *visually process* (VP). He summarizes as follows:

> … IFI involves knowledge of the visual conventions and spatial 'vocabulary' used in geometric work, graphs, charts, and diagrams of all types. Mathematics abounds with such forms and IFI includes the 'reading' and interpretation of these. …VP on the other hand, involves the ideas of visualization, the translation of abstract relationships and non-figural data into visual terms, the manipulation and extrapolation of visual imagery, and the transformation of one visual image into another. (Bishop 1983, p. 177)

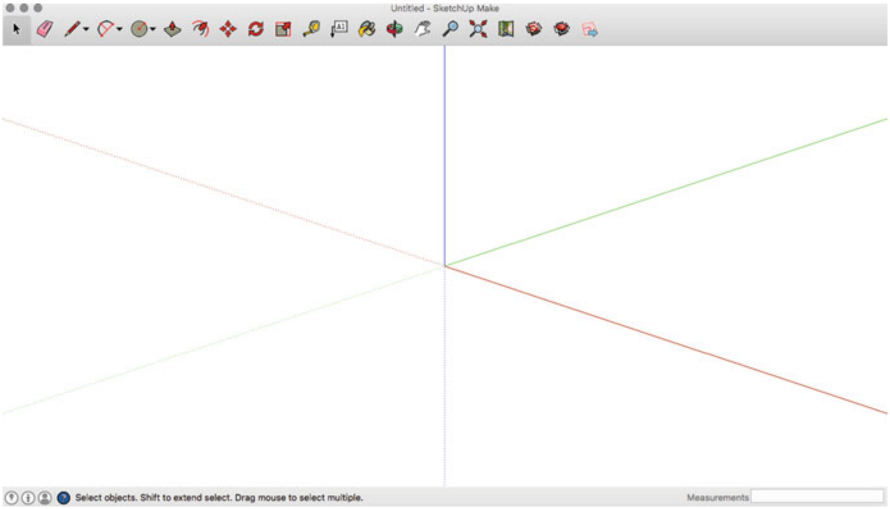
Since, VP refers to the creation and manipulation of mental and dynamic images, and IFI refers not only to converting, using and interpreting such mental and dynamic images to solve a certain mathematical task, but also to using spatial vocabulary in pursuit of the task. Because these abilities provide information about *actions* to be performed, not on skills or sub-skills that one requires for the completion of such an action, as Gutiérrez (1996) discusses, abilities IFI and VP can be described as a 'category of *processes* to be performed' (p. 7). For example, see the following open-ended task (Fig. 9.1).

In this task, a possible way of thinking for subjects to solve the task can be summarized. First, a student uses ready-made geometric figures, cubes and triangle(s), and, thereafter, she/he has to imagine the rear of a building to answer how many cubes could be placed there, for which there are several possibilities. Secondly, the subject can follow reasoning to consider the total area of the building. Consequently, the first process refers to VP and the second refers to IFI. Here, it should be noted that certain specific visual images of Presmeg (1986), in particular, cubes and triangles as *concrete images*, a subject's possible gestures or physical movements of hands and so on, as *kinaesthetic images*, and imagining the rear of the building as a *dynamic image*, could be used and/or created in the VP of the subject. I will consider such visualization-spatial thinking processes to construct a viewpoint looking into subjects' use of 3D modeling software while they are using it as an *artefact*.



Task: *How many unit squares can be the total area of this building*?

Fig. 9.1 A sample spatial task



Select objects. Shift to extend select. Drag mouse to select multiple.

Fig. 9.2 SketchUp® Make interface

9.2.1 *Individuals' Use of SketchUp® Whilst Exploring Spatial Tasks*

SketchUp® is 3D modeling software developed for graphic design, the design of architectural environments and engineering, and also for 3D graphics education. The freeware version is SketchUp® Make, which includes several tools and functions to create various kinds of figures, shapes or models, both in 2D and 3D in its interface (Fig. 9.2).

A full discussion of the functions and tools of the software, with respect to spatial thinking and learning geometry, would be outside the theme of this chapter, but

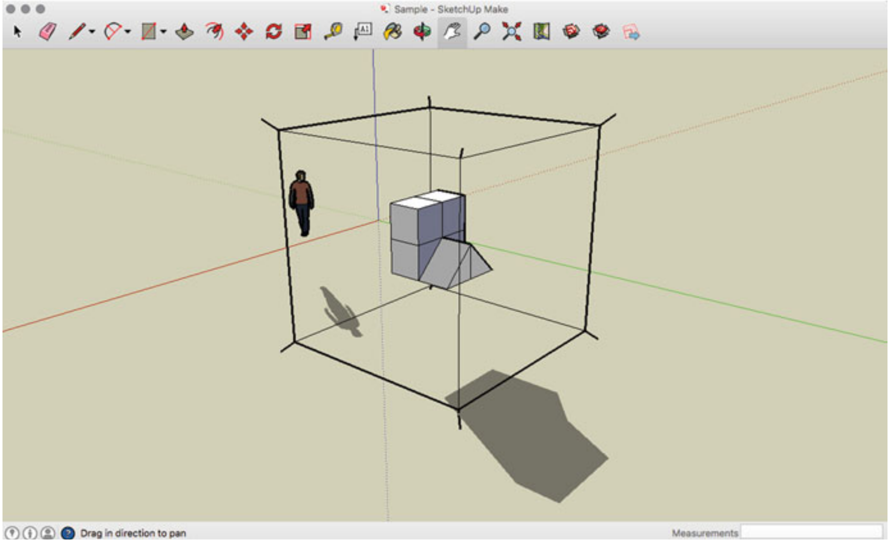


Fig. 9.3 Figures and shadows

I can point out some papers to readers (Fleron 2009; La Ferla et al. 2009; Turgut and Uygan 2013). If one provides users an environment, the tools and functions of the software provide users with an immediate interrelated *imagination* and *visualization* process (Turgut and Uygan 2014). For example, in Fig. 9.3, the user has several functions and tools to analyze where the light is coming from. It is obvious that, in order to explore the proposed task, the user will also join the VP and IFI processes that I postulate and describe above.

Experimental studies indicate the positive effects of educational designs through use of this software on students' spatial skills (Erkoc et al. 2013; Kurtulus and Uygan 2010). I am not interested in such potential in this chapter, but am interested in discussion of a semiotic perspective on how students (as well as the teacher) are using this software. For instance, what kinds of semiotic resources attached to students' use of tools and functions appear while they are thinking spatially? This question brings us to another point; the framing and investigation of a phenomenon relating to signs, spatial thinking and mathematics education.

9.3 Semiotics, Spatial Thinking and Mathematics Education

Semiotics, in the sense of C.S. Peirce, can be labeled as a discipline of science, dealing with *signs*, which mediates a dialectic relationship between an *object* and its *interpretant*. According to Peirce, an interacting triangle of signs or *representamens*, object and interpretant, forms *semiosis*, which is defined by him as:

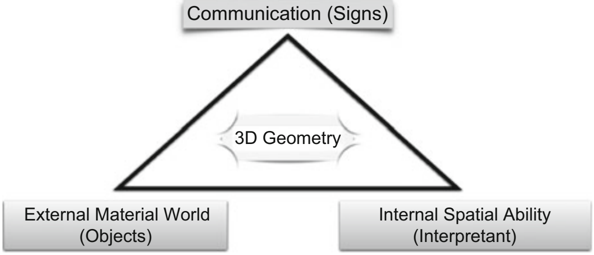


Fig. 9.4 Semiotic triad of 3D geometry (Adopted from Yeh and Nason 2004, p. 4)

> … a sign, or *representamen*, which is something which means something to somebody in some respect or capacity. It addresses somebody, that is, it creates in the mind of that person an equivalent sign, or perhaps a more developed sign. That sign which it creates I call the *interpretant* of the first sign. The sign stands for something, its *object*. (Buchler 2015, p. 99)

For example, a (red) traffic light can be considered as the *sign* or *representamen*, stopped vehicles as the *object*, and the idea that when people see the red light they must stop as the *interpretant* (Chandler 2014). From the cognitive perspective, Peirce notes that, for a meaningful comprehension, *such semiosis process must occur*. Therefore, from a didactical point of view, semiosis gives clues about how meaning-making occurs, which is of great importance, for us as mathematics educators, for an understanding of how the learning of mathematics occurs.

Peirce classifies the signs into three; *icon*, *index*, and *symbol*. An icon(ic) sign refers to physically resembling or imitating the object through a list of equations, graphs, portraits, maps, metaphors, or *gestures* such as imitating hand movements and so on. An index refers to signs that are directly related to the object, but without any similarity or analogy to the object, by which a person (of course *an animal*) can infer an immediate link between the sign and object in terms of sensorial functions. For example, a smiling face may be considered to be an index sign referring to happiness. Symbols refer to signs driven by conventional or virtual rules, such as language, words, numbers, traffic lights and so on.

In context of learning 3D geometry, Yeh and Nason (2004) propose a semiotic framework considering Peircean semiotics, to design a virtual teaching-learning environment, consisting of three main components; *external material world*, *internal spatial ability*, and *communication* (Fig. 9.4).

The external material world refers to all geometric objects, such as patterns and their relationships to shapes, triangles, cubes, a shell or a growing tree, and to their properties. Internal spatial ability refers to the mental process of human potential to know, perceive and manipulate external geometric objects. The communication component refers to signs at large, which includes not only spoken and written language, but also includes 'mathematical notation, pictures, diagrams, kinaesthetic body movements, and even geometric objects themselves' (ibid., p. 5). It is apparent that this framework considers and also exploits the semiosis process in the design of a virtual environment, to construct mathematical meanings through students' exploration of the proposed context in different semiotic representations. However, this framework does not directly focus on the emergence of signs in the spatial thinking process.

A focus on *signs* in spatial thinking (or also in learning geometry) would provide details from both a cognitive and didactic point of view, and also glimpse how students *gesture*, as an *icon sign*, while thinking spatially. There is extensive literature on the elaboration of the relationship between gestures and spatial thinking. I can refer to interesting papers on the subject (Alibali 2005; Atit et al. 2013; Chu and Kita 2008, 2011; Ehrlich et al. 2006; Logan et al. 2014; Ng and Sinclair 2013). In her excellent review, Alibali (2005) concludes that individuals produce gestures more often when talking about spatial topics than when talking about verbal or abstract topics. It can, therefore, be concluded that gestures often accompany spatial language and have a functional role in the process of spatial thinking. As she notes, McNeill (1992) hypothesizes that '… gestures reflect mental images …' and according to this approach '… spatial thinking is integral to gesture production …' (ibid., p. 308). Experimental research studies seem to confirm this notion. For example, Chu and Kita (2011) found that individuals spontaneously produce gestures when they have difficulty with mental rotation tasks, to help themselves solve the task. Chu and Kita also conclude that gestures contribute to performance in spatial visualization tasks, since they improve 'internal computation' of dynamic images while thinking spatially. Recently, the use of gestures by preschool children to communicate mathematically, and to internalize their thinking while they are solving spatial transformation tasks, was also observed (Ng and Sinclair 2013).

Finally, as a general conclusion in the related literature, researchers agree that gestures provide useful information about individuals' ways of spatial thinking as an *internal reference*. However, what about other signs that appear in a teaching-learning mathematics process, such as words, sketches and so on, or signs produced by the teacher? What is the meaning of a student's pre-drawing in solving a spatial task? To my knowledge, there is no framework which looks at the spatial thinking picture in a holistic way of produced signs in the classroom. As mentioned earlier, the framework of Yeh and Nason (2004) does not look at all the signs that are expected to emerge in the spatial thinking process. However, there is a general perspective from the didactics of mathematics (not specifically to spatial thinking) focusing on different kinds of semiotic resources produced in the classroom. I will focus on Arzarello's notion of Action, Production and Communication space (APC-space), which is an extension of other semiotic approaches (e.g., Duval 2006; Ernest 2005); and Arzarello and his colleagues' notion of *semiotic bundle* to cover all the signs that appear in the classroom.

9.3.1 Embodied Cognition, Signs and the Notion of APC-Space

Embodied cognition perspectives hypothesize 'that cognitive processes are rooted in interactions of the *human body* and the *physical world*' (Alibali et al. 2014, p. 150). Our body's interaction with the physical world, while we are trying to express meanings (we have) is in a *multimodal* way, not only limited to gestures, but also includes words, sounds, mimics, sketches and so on, as well as our sensory-motor functions' products (Arzarello and Robutti 2008). Arzarello and Sabena (2014) note that in order to interpret the process of the interaction of human body and ICTs, such multimodal perspective receives increasing relevance in the elaboration of both thinking and communication.

Following a multimodal approach within the embodied cognition, Arzarello (2008) considers a socio-cultural dimension of the teaching-learning process in the sense of Vygotsky and his followers, to frame a new viewpoint looking at processes developed in the classroom and shared by both teacher and students; the *APC—space*. This APC—space has three main components; (i) *the body*, (ii) *the physical world*, and (iii) *the cultural environment*. Inductively, an intersection of such elements in a mathematics classroom will yield a variety of signs, including students' gestures, communications, teacher's discourse, teacher's gestures (also gestures with chalk), graphs (in our case the *use of artefacts*) and suchlike. In order to frame such a variety of signs, Arzarello (2006) introduces the notion of the semiotic bundle, which is re-elaborated by Arzarello et al. (2009):

> A semiotic bundle is a system of signs (with Peirce's comprehensive notion of sign) that is produced by one or more interacting subjects and that evolves over time. Typically, a semiotic bundle is made up of signs that are produced by a student or by a group of students while solving a problem and/or while discussing a mathematical question. Possibly, the teacher also participates in this production, and so the semiotic bundle may also include signs produced by teacher. (Arzarello et al. 2009, p. 100)

The notions of APC-space and the semiotic bundle are powerful frames to describe semiotic activities in the classroom. However, as these paradigms hypothesize, there would appear to be several kinds of semiotic resources in this process. How can we look at such resources to understand mathematical phenomena as a cognitive process? Two different, but complementary analysis units can be employed to the data; (i) a *synchronic analysis*, and (ii) a *diachronic analysis*. The first focuses on 'the relationships among different semiotic resources simultaneously activated by the subjects at a certain moment', and the second analysis looks at 'the evolution of signs activated by the subject in successive moments' (ibid., p. 100). I will try to explain why I consider such notions to examine the spatial thinking process.

9.4 Toward a Spatial-Semiotic Framework in the Context of ICT

Within the context of the chapter, I try to express three main components to describe a viewpoint for the spatial thinking process while students (and the teacher) interact with 3D modeling software; the type of mental image, two interrelated processes of VP and IFI, and the emergence of signs with a multimodal perspective. The related literature promises a link between spatial thinking and gestures. However, I believe that this cannot be limited solely to gestures. For instance, think of a student using SketchUp® to solve and explore the task in Fig. 9.1 (also in Fig. 9.3). I postulate that, first of all, the creation and manipulation of mental images occur in VP. However, in this process, students would consider certain tools and functions of the software; for instance, the 'rotate' or the 'move' tools. The use of these artefacts is an index sign, i.e., an indicator of his/her VP process, and would also possibly be an indicator of the existence of *dynamic images*. While exploration with the artefact, if the student uses specific words, belongs to his/her experience and background in geometry or mathematics, i.e., 'cube', 'triangle' or suchlike, these would be *symbolic signs* referring to *concrete images*. If he/she uses his/her fingers to trace or point something out, this gesture would be a kind of *icon sign* referring to *kinaesthetic images*. Moreover, in such steps, the user may prefer to use his/her spatial vocabulary to read and interpret the visual images that he/she imagines/creates. This process refers to IFI, where the user may also further become involved in a reasoning process. The student may use a paper-pencil form or his/her analyses through the screen, or prefer to use the tools and functions of the software, which are also index signs belonging to his/her reasoning. Also, in this process, the student (also the teacher whilst lecturing) will possibly use certain *specific words*, *gestures*, *sketches* or *specific tools* while interacting with his/her partner or with the teacher. Such interactions would yield different kinds of semiotic resources, i.e., *signs* indicating the existence and creation of concrete, kinaesthetic or dynamic images. Therefore, in summary, my hypothesis is that, *thinking spatially in 3D modeling software is also multimodal*.

The phenomenological analysis above promises to consider a multimodal approach of the notions of APC-space and the semiotic bundle to explain different kinds of signs that appear in the classroom, when tasks and problems are investigated by the community of the classroom, and when the students and the teacher are thinking spatially. I illustrate my hypothesis with the following figure (Fig. 9.5), describing the relationship among VP and IFI processes, the type of mental images and the emergence of signs when the community pursue a task in 3D modeling software.

In this framework, analyses of signs belonging to spatial thinking can be elaborated on through a *synchronic analysis*, and a *diachronic analysis* as Arzarello (2006) and Arzarello et al. (2009) propose. Two examples evaluate and discuss the framework in the following sections.

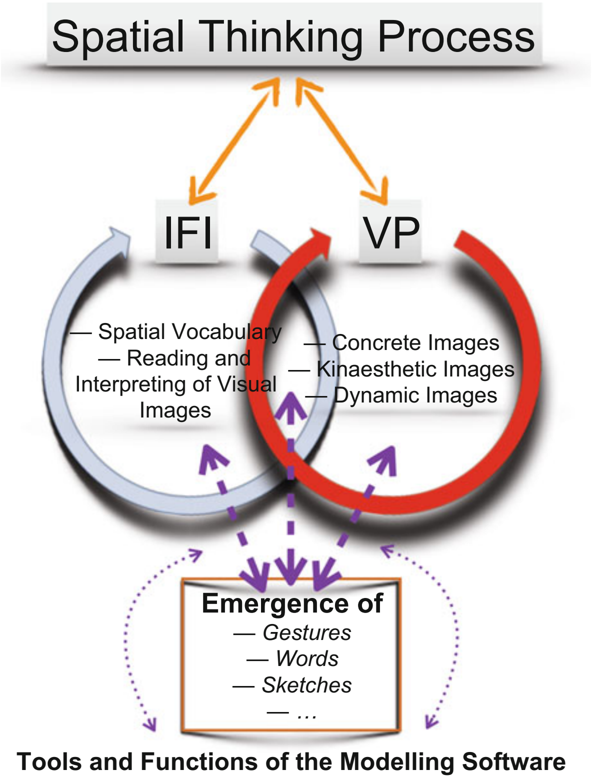


Fig. 9.5 A spatial-semiotic framework in the context of 3D modeling software

9.5 Case Studies

Data for the examples is provided from extensive research carried out with two middle students and a teacher, aiming to analyze the students' instrumental genesis (Vérillon and Rabardel 1995) and the teacher's role in this process. I now consider an item of data from this research to interpret one of the student's and the teacher's spatial thinking processes, while they are interacting with 3D modeling software. The student in this research was selected considering two main criteria; (i) The student's geometry-mathematics performance as evaluated by the teacher, and (ii) his spatial skills analyzed by two spatial tests (for details, see Turgut and Uygan 2015). Following this, Davut (a pseudonym), a seventh grader, was selected to participate. Within the context of the Turkish middle school mathematics curriculum, it should be noted that the student was familiar with basic geometric concepts and their properties, such as triangles, rectangles, squares and so on. The teacher conducting this research had the role of teacher/researcher, when the research was carried out. The teacher had both bachelor and master degrees, and was also a doctoral student in

Fig. 9.6 The first task

mathematics education with a background in the integration of ICT to mathematics education in practice.

With regard to the instrumental genesis window, initially the students involved received training in the use of the SketchUp® for the exploration of the tasks. The teacher introduced basic tools and functions of the software (e.g., top view, pan, select, move, rotate, lines, eraser, rectangle, paint bucket and measurement box) in order to prepare the students for the main application. The students practised two tasks, and thereafter, five main tasks applied, with designs inspired by a doctoral thesis on geographical information systems (Lee 2005). The first task of the main application is outlined in Fig. 9.6. The other four tasks had the same or similar aims, and were designed for the student to use two main sub-skills; mental rotation and mental integration as sub-skills of spatial visualization, according to McGee (1979).

My conviction is that, to introduce 3D modeling software from the window of spatial thinking also needs immediate spatial thinking. First of all, I focus on one element of the teacher's training process, showing how he is thinking spatially while describing the software's functions and tools. Secondly, I look at an interview between one of the students and the teacher to analyze the emergence of signs through a multimodal paradigm. In an synchronic analysis, I only address specific signs belonging to both teacher's and student's spatial thinking processes during the training of the student regarding the software, and with a diachronic analysis, I attempt to elaborate the evolution of signs under VP and IFI processes, i.e., use of spatial vocabulary, reading and interpreting visual images, and the existence of concrete, kinaesthetic and dynamic images. In the overall analyses, I underline specific signs in speech, and will use brackets for gestures or other kinds of signs.

9.5.1 Synchronic and Diachronic Analyses of the Teacher's Training Process

The teacher began to introduce the software and its specific tools in terms of his experience. He expressed that SketchUp® is modeling software is used in engineering fields, but also by practitioners (not professionals) to design 3D models. Thereafter he tried to introduce middle school students to the *x*, *y*, and *z*-axes by

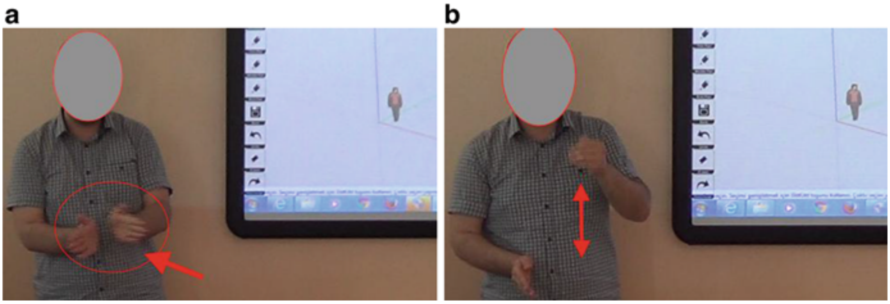


Fig. 9.7 (**a**, **b**) A teacher's gestures describing the coordinate axes

following the interface of the software. Roughly speaking, the semiotic bundle consisted of gestures, sketches, and words. Certain specific signs appear in the introduction to the software, in the process of the teacher's spatial thinking:

Teacher: "… you know the x and y as ordered pairs, right?"
Response: "Yes, …"
Teacher: "Here we have one more … on the plane, while working on the maps, we use latitudes and longitudes to determine exact positions [*gesturing* see Fig. 9.7a], here we have height [*gesturing* see Fig. 9.7b] as the z axis …"

The teacher tries to connect Cartesian geometry and latitudes and longitudes, and for this, he exploits applications of the ordered pair notion using specific gestures, but the description is in relation to the software's interface. He exploits certain references that he (and the students) know; 'maps', 'latitudes and longitudes', 'exact positions' and 'height', which are signs of concrete images in (his) VP. These phrases can also be considered as signs of *specific* (spatial) *vocabulary*, or of his *interpreting the visual images* in his mind, which appears to be related to IFI. Specific gestures also appear that correspond to the xy axes (Fig. 9.7a) and the z-axis (Fig. 9.7b), which can be considered as an attachment of concrete and dynamic images in his VP. To make connection, he also uses his finger by tracing the axes on the software's interface, which is sign of a *kinaesthetic image* in his VP. Later, he begins to introduce one particular tool of the software, the *orbit*, expressing:

Teacher: "… when we look at the interface, it looks two-dimensional, however, it is three-dimensional software, and we will transform the two-dimensional to a three-dimensional working space through the orbit tool" … "In fact, we rotate the whole screen [gesturing Fig. 9.8a] through this, all the objects [gesturing Fig. 9.8b] …"

The teacher tries to introduce students to the notion of 3D rotation on the interface of the software. He uses basic notions of elementary geometry, related to the notion of dimension saying 'two-dimensional' and 'three-dimensional', with particular emphasis on an advanced notion, the transformation ('transform'). These phrases can be considered a manifestation of the teacher's concrete and dynamic images in VP that are related to 2D and 3D thinking in his mind. Moreover, such

Fig. 9.8 (**a**, **b**) A teacher's gestures describing 3D rotation

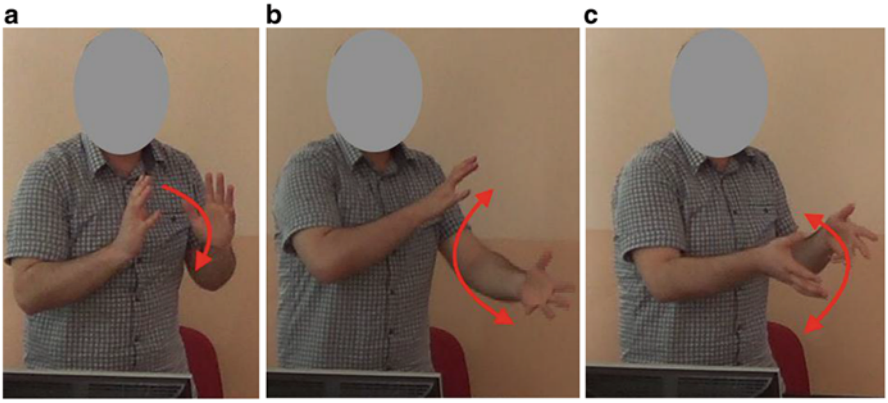


Fig. 9.9 (**a**–**c**) A teacher's gestures during a description of the 'views' function

expressions can also be considered as signs of IFI, because they point out spatial vocabulary. His bodily movements, beyond gesturing, appear to describe this process (see Fig. 9.8 a, b), i.e., the plane view transforms into a 'three-dimensional working space' as a sign of his description of 3D rotation. After the 'orbit' tool, the teacher introduces the 'views' function of the software.

Teacher: "… in terms of the views function, here we can change our viewpoint to top [gesturing Fig. 9.9a], left or right [gesturing Fig. 9.9b] and front or back [gesturing Fig. 9.9c]. For example, looking at a tall building from the outside …"

The teacher relates the views function of the software and, at this moment, gestures appear (Fig. 9.9) that are related to an amalgam of his *spatial orientation* and *mental rotation* skills, which are attached signs of existence of immediate dynamic images in VP. While describing different viewpoints, the teacher uses different

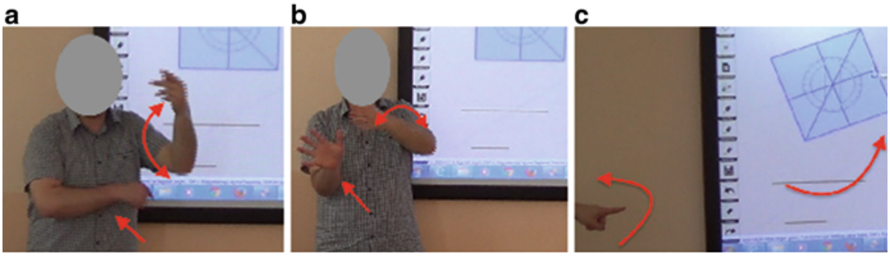


Fig. 9.10 (**a**–**c**) A teacher's gestures describing rotations according to specific axes

gestures to interpret his mental pictures associated with spatial orientation. He also uses underpinning phrases such as, 'our viewpoint', and 'a tall building' as spatial vocabulary referring to IFI. 'A tall building', here, can also be a sign of a concrete image belonging to VP. As a next step, he introduces the 'rotate' tool saying:

> Teacher: "… you may only know how to rotate something on a plane, for example, the rotation of a rectangular piece of paper [imitating with a paper]. Here, we have several rotations, for example, with respect to a square's lengths [gesturing Fig. 9.10a, b] or its centre [imitating with the paper]. … What about the <u>angle of rotation</u>? …"

After introduction of the tool, the teacher shows the role *protractor* on the screen by gesturing with his finger and describing the rotation (Fig. 9.10c). He also connects the rotation angle of the objects with 'reflections' of the objects and, using the orbit tool, he shows the students how 3D rotation can be achieved with respect to different axes. As can be seen in Fig. 9.10a, b, the teacher uses his right hand as the rotation axes, with his left hand imitating the rotation. All these gesture signs may be evidence of his dynamic images of rotations, while 'rotating something on the plane' and 'rotation of a rectangular piece of paper' can be considered as signs of concrete images in VP. These, as well as the phrase 'angle of rotation' seem related to the spatial vocabulary of IFI. The teacher's imitation of the paper and immediate sketches on the screen can be also considered as signs of his VP and IFI.

9.5.2 Synchronic and Diachronic Analyses of the Student's Exploration of the Tasks

The interview begins with the teacher introducing the task to the student. At first, Davut (interestingly) uses the mouse pointer to describe what he should do:

> Davut: "… the <u>rotation axis</u> is fixed? … This square [*pointing to the right figure with the mouse cursor*] <u>should be rotated 90°</u> clockwise, and this square [*making a rotation imitation with the mouse cursor clockwise*] <u>should be rotated 180°</u> … [*he completes the steps with the tools*]"
>
> …
>
> Davut: "… this [*gesturing* Fig. 9.11a] <u>should be rotated 180°</u> [*gesturing* Fig. 9.11b], and this [*gesturing*] will not change; it will remain itself. Finally I must overlap them …"

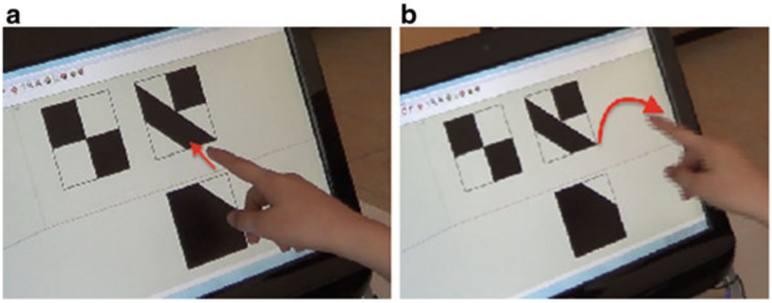


Fig. 9.11 (**a**, **b**) The student Davut's pointing gestures during the second task

Fig. 9.12 (**a**–**c**) The student Davut's pointing cursor and finger gestures

Davut has dynamic images associated with the positions of the figures, and completes the rotations in his mind, apparent by the signs he makes by mimicking through the mouse cursor as evidence of VP to complete mental rotation and mental integration. In addition, the underlined phrases seem to confirm this. Besides, he is now aware the given objects can be rotated with respect to different axes, he asks about the 'rotation axis', which can be considered a sign of IFI. After this, he completes the task using mental images. In the second task, Davut's gestures appear to describe the rotation, and this can be considered as a sign of attachment to his dynamic images, as in the previous task. Interestingly, in the fourth task which is similar to the others, he uses anti-clockwise rotations, although in the task a clockwise rotation is stated, with these signs providing the existence of dynamic images in his VP. He is interpreting the visual image, which is also a sign of IFI.

In the fifth task, the teacher provides three figures and asks how he should manipulate two, to obtain the final figure. However, this task can be tricky, because the final task cannot be achieved in terms of given two's manipulations. Davut explores the task, with the following excerpt drawn from this discussion:

Davut: "… the right figure should be rotated 180º … the left one …"
Teacher: "How did you decide this?"
Davut: "I figured it out from this part [*pointing with the mouse cursor*] of the given figure"

Teacher: "What about the other figure?"

Davut: "… there may be some missing parts here [gesture *pointing to the figure*, see Fig. 9.12a], there may be a problem?"

Teacher: "Why are you thinking like that?"
Davut: "There is a missing part here [*rotating the left figure*], these figures do not form [*pointing with fingers* see Fig. 9.12b] the final figure whatever I do, even if I try different angles or different rotation axis"

The dynamic images that Davut created provide him with a glimpse of tricky. He uses the concrete images in his mind to disintegrate parts of the figure. He also uses the mouse cursor instead of his finger, which can be accepted as the existence of a kinaesthetic image. With the underlined phrases, all these signs, they together confirm his VP in solving the task. Moreover, he also expresses all possibilities, such as 'different angle' and 'different rotation axis', which can be considered as an IFI process.

9.6 Conclusions

In this chapter, I propose a spatial-semiotic framework based on a hypothesis that *thinking spatially in a 3D modeling software environment is multimodal*, i.e., thinking spatially is a complex process including different kinds of semiotic resources, such as gestures, sketches, words, imitations, and suchlike. The theoretical underpinnings of the framework were due to VP and IFI processes (Bishop 1983), concrete, kinaesthetic and dynamic images in spatial thinking (Presmeg 1986, 2006), and Peircean semiotics, multimodal paradigm, notions of APC-space and the semiotic bundle in mathematics education (Arzarello 2006, 2008; Arzarello et al. 2009). The results of the case studies were promising regarding the framework. The cases reveal that the emergence of signs was in coordination, i.e., the signs were in relation to the software's tools and functions (see Fig. 9.8a, the teacher's body movements for the orbit tool) as expected. With respect to the signs in such a process, there was a semiotic bundle consisting of three main components; words, gestures and sketches, which confirm (but not always) the framework's hypothesis. Evidently, in the first case, the emergence of signs that confirm the framework's hypothesis was clearer compared to the second case. This may be due to several reasons. The first may be the teacher's background in mathematics, as a mathematics teacher. He used different careful examples showing his thinking with his experience of the software. However, in the student's case, some gestures were interlaced with the mouse's cursor (see Fig. 9.12a). This could be a gesture describing a semi-circle embedded in the given figure. This could also be related to the student's communication skills.

The second reason could the fact that I looked at the data myself. I analyzed the data through my phenomenological experience in the spatial thinking field based on two interrelated viewpoints; (i) my experience in SketchUp®, and (ii) my participation to the training process and interviews. A cross analysis between an insider's and an outsider's viewpoints could provide more detail for a clearer understanding of the observed phenomenon.

The third reason may be the limitation of the tasks with 2D spatial thinking including mental rotation and mental integration. Although the teacher's training includes 3D interface, in this chapter, I could not provide 3D spatial tasks to focus the students' spatial thinking processes within the context of 3D modeling software. In addition, 2D tasks were apparently not related to a type of reasoning in mathematics. Therefore, an elaboration of spatial thinking in solving 3D geometry tasks could provide different kinds of semiotic resources to evaluate or ameliorate the proposed framework. For this purpose, dynamic geometry environments (DGEs), for example Cabri, GeoGebra, Sketchpad and suchlike, with dragging functions to provide the user various kinds of epistemic situations to explore the provided tasks, could be used (Leung 2008; Leung et al. 2013; Lopez-Real and Leung 2006). Such DGEs could be designed as a tool of semiotic mediation (Bartolini Bussi and Mariotti 2008) to also look at the construction of mathematical (meanings) signs in the solution of tasks. More information attached to the IFI process of students could be helpful in reanalyzing the function of the framework, in the interpretation of the obtained data in depth. Consequently, I note that this fresh framework requires more elaboration. For example, one might discuss the role of geometric reasoning (Duval 1995, 1998) or geometric space work (Kuzniak 2014) in the functioning of the framework. This may be possible through strategies of networking theoretical frameworks elaborated by Prediger and Bikner-Ahsbahs (2014).

It is clearly stated in the related literature that spatial thinking predicts achievement in Science, Technology, Engineering and Mathematics (STEM) fields (Kell and Lubinski 2013; Shea et al. 2001; Wai et al. 2009). Therefore one can conclude that development of spatial ability—because it is malleable (Stieff and Uttal 2015; Uttal et al. 2013)—might contribute the improvement of achievement in STEM fields. In this respect, how the present spatial—semiotic framework will function in the analyzing the role of spatial ability in STEM fields can be summarized as follows.

This fresh framework enables researchers not only look at the emergence of signs when the subjects commence ICTs and while they are thinking spatially, but also provides a detailed understanding of the teacher's spatial thinking process. Such kind of analyses in the teaching–learning process could be a potential tool to investigate the subjects' *internalization* and/or *externalization* of spatial images. Such variety of specific signs such as gestures, sketches and/or words that attached to *creation* and *manipulation of spatial images* could provide an understanding of the subjects' way of spatial thinking in the use of ICTs. More specifically, framework has two interrelated dimensions: IFI and VP, and emergence of the attached signs in the use of ICT tools. In the use of this framework, researchers could gain a lens for a better understanding the subjects' thinking process in depth, because it provides the subjects' use of *spatial language*, their *interpretation* of the visual–spatial images, and their use of concrete, kinaesthetic and dynamic images together with the functions and tools of ICTs. In the light of this, researchers could create affective pedagogical designs to improve spatial ability and therefore a better achievement in STEM fields.

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Chapter 10
Gender Differences in Spatial Ability: Implications for STEM Education and Approaches to Reducing the Gender Gap for Parents and Educators

David Reilly, David L. Neumann, and Glenda Andrews

10.1 Introduction

10.1.1 Overview of Gender Differences

The existence of gender differences in cognitive ability is a controversial topic. Nevertheless, researchers in psychological and the social sciences widely acknowledge that males and females differ in spatial ability (Halpern and Collaer 2005; Kimura 2000). Indeed, it is one of the most robust and consistently found phenomenon of all cognitive gender differences (Halpern 2011; Voyer et al. 1995). While there is individual variability within each gender, on average males score higher than females on tests that measure visual-spatial ability. However, there is considerable debate over just how large the differences between males and females are. Researchers also differ in their perspectives on the origins of the gender differences, including the relative contributions of biological, social and cultural factors. This chapter provides an overview of the research literature, as well as covering the developmental and educational implications for children.

Many researchers posit that early expertise in spatial ability in children lays down a foundation for the development of quantitative reasoning, a collective term encompassing science and mathematics. These researchers argue that the early differences in spatial ability have important implications for student achievement in STEM (science, technology, engineering and mathematics) subjects, and may partially explain the underrepresentation of women in science. However, while some

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children may be naturally gifted in spatial ability, there is a large body of research showing that spatial proficiency can be improved through relatively brief interventions. A growing number of educational psychologists have argued that early education of spatial intelligence is necessary as a matter of equity for all students, and that it may offer substantial benefits for the later development of mathematical and scientific skills across all ability levels (Halpern et al. 2007). We review interventions aimed at increasing spatial aptitude, and the role of parents and teachers in encouraging the development of these abilities.

10.1.2 What Is Spatial Ability?

The term “spatial ability” (also referred to in some research as visuospatial or visual-spatial ability) encompasses a range of different skills and operations, so it is important to clearly define the term. Laypeople can sometimes use the term very loosely, covering anything from block building assembly to reading maps and navigating one’s way around the city streets. Such tasks often incorporate additional (non-spatial) processes, including memory and general problem solving skills. Psychologists and cognitive researchers apply the term spatial ability to tasks that are intended to measure specific cognitive processes in isolation. Linn and Petersen (1985, p. 1482) defined spatial ability as the “skill in representing, transforming, generating and recalling symbolic, non-linguistic information”. More generally, it is the ability to perceive and understand spatial relationships, to visualize spatial stimuli such as objects, and to manipulate or transform them in some way – such as mentally rotating an object to imagine what it might look like viewed from a different angle or perspective. Spatial ability is crucial to a wide variety of traditional occupations including architecture, interior decorating, drafting, aviation, as well as a growing number of new and emerging occupations in the science and technology fields.

Spatial ability encompasses a broad range of cognitive processes, with the size of gender differences varying depending on the type of task (Voyer et al. 1995). When measuring spatial ability, some tasks measure global spatial skills such as wayfinding and navigation in virtual environments or outside the laboratory (Lawton and Kallai 2002). More commonly, specially designed tasks are employed to tap one or more spatial components in isolation. Linn and Petersen (1985), in a pioneering review of the literature, outlined three distinct categories of spatial ability. Firstly, we have *spatial perception*, which involves perceiving spatial relationships. A commonly employed task of spatial perception is Piagetian Water Level Task, which requires individuals to draw the waterline on a variety of containers or bottles that have been tilted a certain number of degrees (see Fig. 10.1). Another is the Judgment of Line Angle and Position test (JLAP), which requires subjects to correctly judge the orientation of a series of tilted lines (see Fig. 10.2).

The second category of spatial tasks is *mental rotation*. Tasks measuring mental rotation involve requiring individuals to mentally rotate spatial objects to see how they would look from a different angle or perspective (see Fig. 10.3). Mental rotation

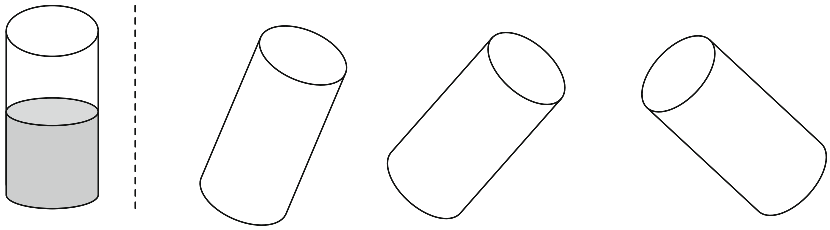

Fig. 10.1 In the Piaget water level task (Vasta and Liben 1996), subjects are presented with a container of liquid (*left*), with varying quantities of fluid. The container is then tilted adjacent to the horizontal plane. Subjects must then draw a *line* to indicate the probable water line in each of these containers

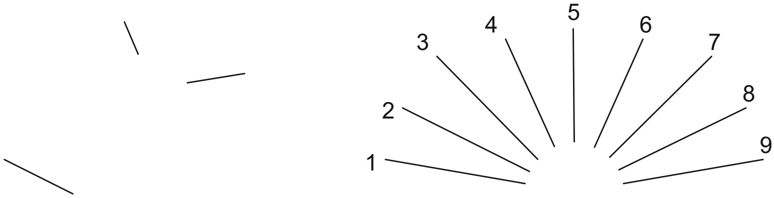

Fig. 10.2 Representative stimuli for judgement of the Judgment of Line Angle and Position test (JLAP; Collaer et al. 2007). Subjects must match the orientation of stimuli lines (*left*) to a reference array (*right*). The correct answers from left to right are 2, 4 and 9

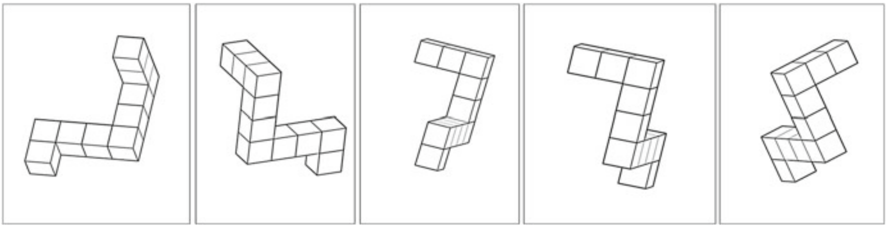

Fig. 10.3 Sample stimuli from the Vandenberg mental rotation task (Vandenberg and Kuse 1978). Subjects must locate both instances of the target shape (*left*) amongst the four possible choices. Two of the choices are mirror image distractors. To answer the question correctly, both targets must be located. The correct answer is 1 and 3 (From Peters and Battista (2008). Used by permission)

tasks usually involve three dimensional stimuli (Kimura 2000), though some tasks use less complex two dimensional stimuli (Prinzel and Freeman 1995).

The third category of spatial ability is *spatial visualization* which involve more complicated multistep manipulations of spatial information in order to reach a solution. These tasks often incorporate some element of spatial perception and mental rotation. They are distinguished by having multiple solution strategies for reaching a solution. Common tests of spatial visualization include the Embedded Figures

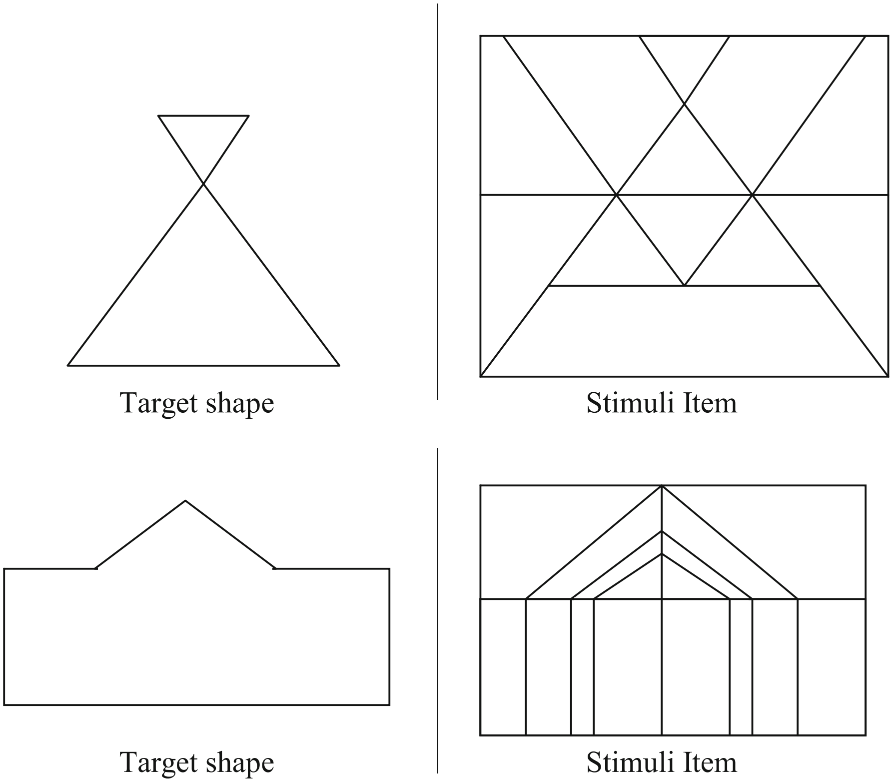

Fig. 10.4 Spatial visualization items representative of those used in embedded figures tasks (Witkin 1971). Subjects are asked to locate a target shape (shown on the *left*) within a more complex picture (*right*)

Test (EFT; see Fig. 10.4), which requires individuals to search for a target shape within a more complex picture of geometric shapes and to ignore distracting visual information. Another task is the Paper Folding task, which requires individuals to visualize how a sheet of paper would appear if it were folded in a certain way and then one or more holes were punched through the folded sheet. Individuals must indicate how the unfurled paper would appear and indicate the position of dots from a series of possible answers (see Fig. 10.5).

Some researchers have proposed a fourth category called *spatiotemporal ability*, which involves making time-to-arrival judgments or tracking the movement of an object through space (Hunt et al. 1988). Such tasks are computer administered in order to accurately measure response times and determine whether there are discrepancies between projected and actual arrival time (see Fig. 10.6). Other tasks involve directing the path of multiple objects concurrently (see Fig. 10.7; Contreras et al. 2001, 2007). However, it is unclear whether the gender difference observed with these tasks is necessarily spatial in nature, because there is some evidence that

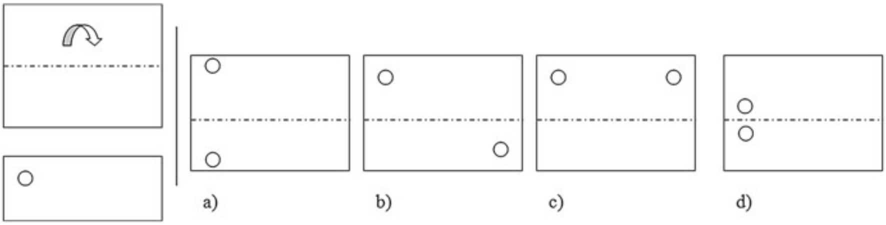

Fig. 10.5 Representative stimuli for a paper folding task (French et al. 1963). On the left, we have a blank sheet of paper with the fold line indicated (*top-left*). A hole is punched through the folded sheet of paper (*bottom-left*), and then subjects are asked to indentify which of the choices would represent the unfurled paper. Correct answer is d)

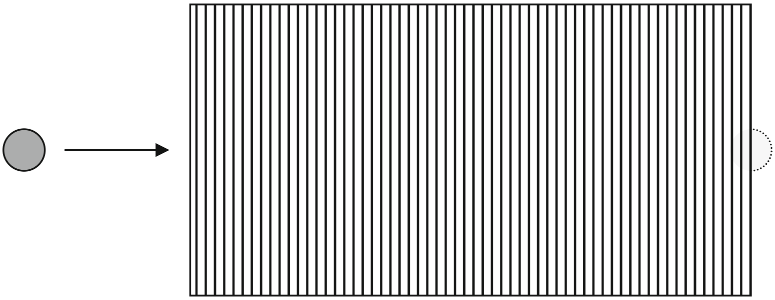

Fig. 10.6 An example of dynamic spatial ability task proposed by Hunt et al. (1988) requires subjects to judge the velocity of a target object as it moves behind an obscured view, and to press a key when they believe the object will emerge

males are more accurate in time perception generally (Hancock and Rausch 2010; Rammsayer and Lustnauer 1989).

10.1.3 *Statistical Methods for Evaluating Gender Differences in Research*

Experiments in psychology make heavy use of sampling, as it would be impractical to collect a measurement from *every* member of a given target population.

When a sufficiently large number of people are recruited, statistical tests can be performed to determine the probability that the observed group differences are due to chance, or whether they are likely to be found again if the experiment was repeated. If the probability that the results of the study occurred by chance is very low, the result is said to be *statistically significant*. Because research involves volunteer participants giving up their valuable time, and the time of the investigator to supervise data collection, researchers generally seek to minimise the number of participants involved. When extremely small sample sizes are recruited for a study

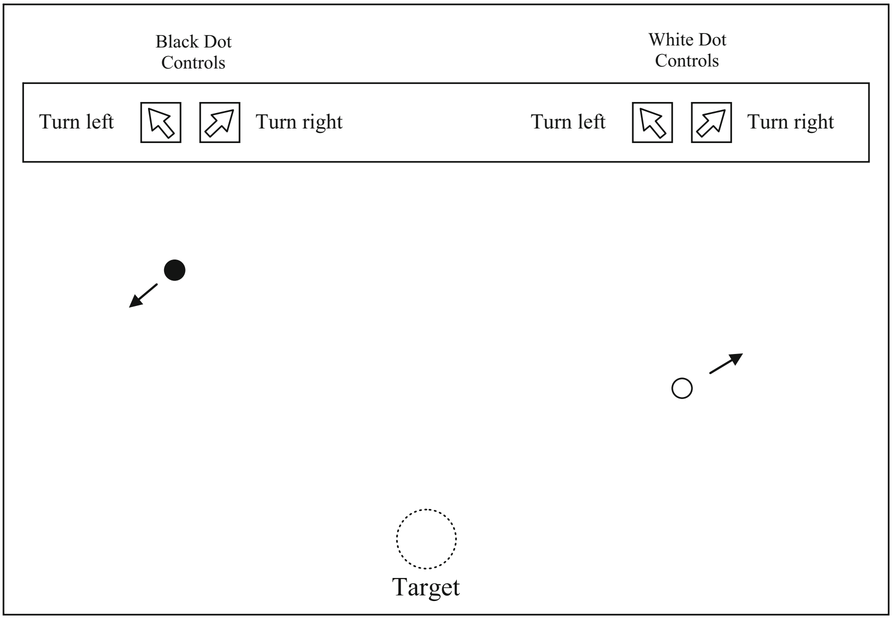

Fig. 10.7 Dynamic spatial ability requires subjects to steer two concurrently moving objects to a fixed destination point by clicking on the turn left and turn right buttons. *Arrows* show motion path of the *black* and *white dots*. Representative of the Spatial Orientation Dynamic Test – Revised (SODT-R; Contreras et al. 2007)

it may be lacking in statistical power (the ability to detect a statistically significant effect in a given sample, if indeed the effect in question is genuine). Furthermore, samples may differ in important characteristics, such as age, socioeconomic status, level of education, which may affect the study outcomes, serving to increase or diminish the magnitude of any group differences between males and females. By pooling the data from many studies, statistical power is increased and the researcher can arrive at a more reliable estimate of the true size of a given effect than could be reached from any individual study.

Meta-analysis is a statistical technique employed to summarize research findings across studies. Meta-analysis uses statistical methods to quantify effects across studies in an open and transparent manner, rather than simply comparing the tally of positive to negative studies (referred to as 'vote counting') or presenting a subjective interpretation of the scientific literature. For example, a selective review of spatial literature by Caplan et al. (1985) made the surprising claim that gender differences in spatial ability were diminishing and were no longer reliably found. A subsequent meta-analysis by Linn and Petersen (1985) provided strong quantitative evidence in a review of the *entire* published literature of the time that refuted such claims. Statistical techniques and software have advanced sufficiently in recent times so that it is now possible to test additional hypotheses about potential moderators, such as whether gender differences are diminishing in size across decades, or whether gender differences are present at certain developmental ages (such as childhood and adolescence).

When comparing two groups (such as males and females), the size of the effect in question is represented using a metric. A commonly used metric is Cohen's *d*, which represents the mean difference between two groups divided by the pooled standard deviation. The use of a common metric facilitates comparisons across different types of tests and samples, in a way that just reporting the mean difference could not. Cohen (1988) offered a set of guidelines for interpreting the magnitude of these group differences, suggesting that an effect size of $d < 0.20$ could be considered a "small" effect, values of approximately 0.50 could be considered medium in size, and values of 0.80 or greater would be considered large in magnitude. These benchmarks offer even the non-statistician assistance in determining whether the effect in question is *practically significant*, holding research to a higher standard than statistical significance alone.

10.1.4 How Large Are Gender Differences in Spatial Ability?

The meta-analytic review conducted by Voyer et al. (1995) represented the most comprehensive meta-analysis of the research on gender differences in spatial ability published at that time. The review categorised tasks by age, comparing children (under 13 years), adolescents (13–18 years), and adults (over 18 years). Mental rotation tasks showed the largest gender differences ($d = 0.33$ for children, $d = 0.45$ for adolescents and $d = 0.66$ in adults) followed by spatial perception ($d = 0.33$ for children, $d = 0.43$ for adolescents and $d = 0.48$ in adults). Spatial visualization showed the smallest gender differences ($d = 0.02$ in children, growing to 18 for adolescents and $d = 0.23$ in adults). By Cohen's guidelines, these would be medium-sized gender differences for mental rotation and spatial perception and in the case of spatial visualization tasks, relatively small. Contrary to earlier claims (e.g. Caplan et al. 1985), there is little substantive evidence that gender differences in visual spatial ability have greatly diminished over time though. Furthermore the gender differences follow a developmental progression from relatively small gender differences in childhood towards much larger gender differences in adolescence and adulthood. Though a meta-analysis has not yet been conducted on the type of spatial task called spatiotemporal ability, effect sizes in such studies typically fall in the medium to large range also (Halpern 2000).

10.1.5 When Are Gender Differences in Spatial Ability First Observed?

Gender differences in spatial ability are observed early. Children in primary school show meaningful differences across a range of spatial tasks including mental rotation and spatial transformation (Lachance and Mazzocco 2006; Levine et al. 1999). Indeed, some studies have even observed small sex differences in young infants when simplified tests of spatial reasoning are employed (Moore and Johnson 2008; Quinn and Liben 2008). However, the gender gap in spatial ability does appear to widen around the time of puberty, which some had claimed supported arguments for a biological and hormonal contribution. Correlation by itself does not necessarily prove *causation* though, as there may be other factors that co-vary with puberty. For example, as developmental researchers would also point out, this is time of increased gender conformity and strengthening of sex-roles (Ruble et al. 2006), as well as greater gender differentiation in play and leisure activities which provide opportunities to practise spatial skill (Baenninger and Newcombe 1989). Even after puberty the gender gap continues to widen, with somewhat larger effect sizes found in adults than adolescents. There is evidence that input and practice is required to fully develop spatial ability (Baenninger and Newcombe 1995), and the increase noted in puberty and in later adulthood may reflect the accumulation of social influences across time rather than the influence of hormonal changes.

10.2 Spatial Ability and Quantitative Reasoning

Spatial ability is thought to underpin the development of quantitative reasoning skills such as mathematics and science (Nuttall et al. 2005; Uttal et al. 2013b), which are important educational objectives. Factor analysis (a statistical technique used to investigate the relationship between tests) of cognitive ability tests show high loading for mathematical performance against a spatial factor (Bornstein 2011; Carrol 1993; Halpern 2000). Wai et al. (2009) note that a large body of research over the course of over 50 years has established that spatial ability plays a crucial role in stimulating the development of quantitative reasoning skills. For example, spatial reasoning is important for understanding diagrams of complex scientific concepts and principals, but individual differences in spatial ability predict learning outcomes with such media in physics and chemistry (Höffler 2010; Kozhevnikov et al. 2007; Wu and Shah 2004). When engaging in complex problem-solving tasks in science and mathematics, students who use spatial imagery and diagrams perform better than students using verbal strategies (Spelke 2005), and growth in spatial working memory is positively correlated with mathematics proficiency (Li and Geary 2013).

Furthermore, performance on measures of spatial ability are predictive of future scholastic achievement in mathematics and science, even many years later (Uttal et al. 2013b). Shea et al. (2001) reported the results of a 20 year longitudinal study that followed children from seventh grade through to the age of 33. They found that individual differences in spatial ability measured in adolescence predicted educational and vocational outcomes two decades later, even after controlling for pre-existing mathematical and verbal abilities.

Another study by Casey et al. (1995) examined a large sample of U.S. adolescents preparing to sit the Mathematics Scholastic Aptitude Test (SAT-M) for college entry, an important prerequisite for entry into further education in mathematics and science. Performance on the Vandenberg Mental Rotation Task successfully predicted SAT-M entrance scores, even after controlling for general scholastic ability (Casey et al. 1995). Although still significant for males, the relationship between spatial ability and mathematics achievement was stronger for females suggesting that girls may be particularly disadvantaged by deficits in spatial reasoning. Casey et al. suggest that spatial ability acts as an important mediator in the gender gap in STEM achievement. Furthermore, they found that higher spatial ability was associated with greater self-efficacy beliefs about learning mathematics (Casey et al. 1997). Attitudes may exert a powerful influence on whether students decide to undertake further classes in mathematics and science (Ferguson et al. 2015; Simpkins et al. 2006), suggesting that there may be motivational effects as well as cognitive effects when spatial competencies are improved.

10.2.1 Importance of Spatial Ability for STEM

Educators, scientists, and policy makers acknowledge the importance of increasing mathematical and science literacy proficiencies for students generally. There is also evidence to suggest that the early gender differences in spatial ability may contribute to the later emergence of gender differences in mathematics and science (Ceci et al. 2009; Wai et al. 2009). Examination of historical scholastic achievement scores in the U.S. by Hedges and Nowell (1995) found that males, on average, have higher achievement scores in mathematics and science. Furthermore, when we examine the extreme right tail of the ability distribution, the gender gap is considerably larger. More recently, studies on data from the federal National Assessment of Educational Progress (NAEP) in the United States replicated these findings. For example, Reilly et al. (2015) observed small but stable mean gender differences in mathematics and science achievement and that at the higher levels of achievement boys outnumber girls by a ratio of 2:1 (Reilly et al. 2015). However gender gaps in maths and science are not inevitable. International assessments of educational achievement find that in some countries, females actually outperform males to a significant degree in mathematics and science (Else-Quest et al. 2010; Guiso et al. 2008; Reilly 2012).

A number of researchers have proposed that in order to address the gender gap in mathematics and science achievement, it is necessary to first address the gender gap in spatial ability (Halpern 2007; Newcombe 2007). Fortunately spatial ability is not a fixed and immutable trait (see the section “Interventions for Training of Spatial Ability”). In a review of educational research on gender difference, Hyde and

Lindberg (2007) argued that even a mild increase in spatial ability might have "multiplier effects in girls' mathematical and science performance" (Hyde and Lindberg 2007, p. 29). This is an important goal as a matter of gender equity, but we can also see substantial improvements of training for males as well. In a review of the developmental and educational research on spatial ability and STEM and the American educational system, Uttal et al. (2013b) argue that including spatial thinking in the science curriculum could substantially increase the number of students capable of pursuing STEM careers. Given that in many developed countries there are shortages within STEM occupations, addressing spatial proficiency in early education may be an important tool for improving overall mathematics and science literacy.

10.3 Theoretical Perspectives on Origins of Gender Differences

Halpern and Collaer (2005) described gender differences in spatial ability as some of the largest found for any cognitive task, raising the important question as to its developmental origins. Why do males on average outperform females on spatial tasks? Past approaches to this question have emphasized biological factors as well as social factors, cultural influences, and life experiences. It is unlikely that there is one single factor that can adequately explain the magnitude of the gender gap for spatial ability. Most gender difference researchers would acknowledge both biological and social forces contribute to their development, embracing a biopsychosocial model of gender differences (Halpern and Tan 2001; Hyde 2014). While there may be biological factors that predispose an individual to greater or lesser proficiency on spatial tasks, it must be remembered that they are not immutable. Full development of such skills requires practice and experience, and both males and females can make significant gains with training.

10.3.1 Evolutionary and Genetic Factors

Evolutionary psychology seeks to make sense of gender differences in human cognition by considering the role of evolutionary selection arising from the division of labour between men and women in traditional hunter-gatherer societies (Eagly and Wood 1999; Geary 1995). Men would be required to travel long distances in order to track and hunt animals, a task requiring strong spatial perception and navigation skills (Buss 1995, 2015). In contrast, women fulfilled the role of the gatherer of more local food and assumed childrearing duties. This role had less need for spatial proficiency but emphasized other adaptive traits such as nurturing and fine-motor skills. Over successive generations, evolutionary forces may have developed sex-specific proficiencies in spatial ability, giving males a strong advantage over females with such tasks (Buss 2015; Jones et al. 2003).

Support for the position of evolutionary psychology comes from cross-cultural studies of cognitive gender differences. Unlike language and quantitative reasoning which shows substantial variation across countries and cultures (Else-Quest et al. 2010; Lynn and Mikk 2009; Reilly 2012), a large body of research has shown that spatial differences are consistently found in all countries (Janssen and Geiser 2012; Peters et al. 2006). Furthermore intelligence – including spatial ability – is a highly heritable trait (Bratko 1996; Sternberg 2012), meaning that it can be passed down from one generation to the next. Nevertheless, some researchers question the validity of evolutionary and genetic factors (Hyde 2014), arguing that at the genetic level men and women are identical with the exception of the sex chromosome. Such arguments do not take into account other biological differences. For instance, the expression of sex hormones might be an important factor linked to genetic and evolutionary gender differences (Hines 2015a; Sherry and Hampson 1997).

10.3.2 Contribution of Sex Hormones to Spatial Ability

Sex hormones such as androgens and estrogens have been proposed as a biological explanation for observed gender differences in spatial ability (Kimura 1996, 2000; Sherry and Hampson 1997). While both males and females produce these sex hormones to some degree, greater androgen production is typically found in males while greater estrogen and progesterone production is present in females. Such a difference starts early, with differences in testosterone concentration of foetuses found as early as 8 weeks gestation (Hines 2010). Production of sex hormones greatly increases with the onset of puberty (Spear 2000), and is associated with a range of psychological and behavioural changes as well as differences in brain development (Berenbaum and Beltz 2011; Sisk and Zehr 2005).

Even before birth, sex hormones contribute to the organisation and development of the brain with lasting effects on behaviour and interests for children (Hines 2015a). Girls exposed to higher than normal levels of androgenic hormones prenatally, either due to a genetic disorder such as congenital adrenal hyperplasia or because androgenic hormones were prescribed to mothers during pregnancy, show increased male-typical play, behaviour, and interests as young children (Auyeung et al. 2009; Hines 2010). Furthermore, they perform at a higher level on tasks of spatial ability than their same-sex peers (Puts et al. 2008). Because spatial ability requires environmental input for development, toys and play can be an important source of spatial experiences. Many stereotypically masculine activities such as construction blocks and model building promote spatial development (Caldera et al. 1989; Caplan and Caplan 1994), and gender differences in sex hormones may influence boys and girls play preferences.

Sex hormones also play an activational role in human behaviour and cognition after the onset of puberty (Berenbaum and Beltz 2011; Spear 2000), which coincides with a widening of the gender gap in spatial ability (Kimura 2000; Voyer et al. 1995). There is an intuitive appeal to considering hormones as explaining part or all of the gender gap in spatial ability, but correlation by itself does not prove causation. Hormonal effects also coincides with increased gender conformity pressures for adolescents (Ruble et al. 2006) which may limit the interests and leisure activities that boys and girls pursue. These, in turn, may provide greater exposure to spatial experiences for boys than girls, thereby exacerbating gender differences.

To establish the causal effects of hormones would require an experiment whereby androgens were administered, which would be both impractical and unethical in developing children. There are instances where researchers have observed the effect of atypical levels of sex hormones (either reduced or increased levels) that are associated with certain medical conditions. Spatial ability in men diagnosed after puberty with hypogonadism is lower than in those with normal testosterone levels (Alexander et al. 1988; Hier and Crowley Jr. 1982), while men receiving hormone replacement therapy later in life showed significant improvements in spatial performance after treatment (Janowsky et al. 1994). In otherwise healthy individuals, some studies have also found a contribution of endogenous testosterone in the bloodstream to spatial performance in both genders (Davison and Susman 2001; Hausmann et al. 2009; Hromatko and Tadinac 2007), as well as fluctuations across the menstrual cycle in girls (Hausmann et al. 2000; Kimura and Hampson 1994). However, not every study finds robust associations (Puts et al. 2010), and the activational role that these hormones play may explain a much smaller proportion of variance in spatial ability than their earlier contribution to brain development (Falter et al. 2006).

10.3.3 Different Socialisation Experiences Between Boys and Girls

While biological contributions to spatial ability may explain some of the gender gap, many researchers argue that gender differences in early socialization experiences of boys and girls also play a significant role. Although there is certainly a contribution of biology, many theorists note that gender is socially constructed. From infancy and throughout childhood and adolescence, boys and girls experience the world differently, and are subject to different pressures and expectations (Lytton and Romney 1991; Martin and Ruble 2004). Boys and girls receive different messages about the suitability of particular toys from their parents, and elicit different styles of interaction during shared play with their parents, caregivers and siblings (Caldera et al. 1989). Children also acquire messages about gender expectations from their peers, and from their teachers and instructors once they have entered the educational system (Jacobs et al. 2002).

There are many different theoretical perspectives on the socialization of gender. For example, social-role theory proposes that psychological differences between men and women arise from gender segregation in men and women's social roles (Eagly and Wood 1999), while the social cognitive theory of gender development posits that gender development is the result of learned experiences that teach gender roles through a system of observation, reinforcement, and punishment (Bussey and

Bandura 1999). An exhaustive coverage of the many other theoretical perspectives on gender is beyond the scope of this chapter, so we highlight only those relating specifically to spatial ability.

10.3.4 Sex-Role Mediation Theory of Spatial Ability

As children develop, they acquire stereotypically masculine or feminine traits, behaviours and interests, a developmental process referred to as sex-typing (Kohlberg and Ullian 1974; Martin and Ruble 2010). However, there is also wide variability across individuals in the degree to which people integrate masculine and feminine traits into their self-concept and sex-role identity (Bem 1981; Spence and Buckner 2000). Highly sex-typed individuals are motivated to keep their behaviour and self-concept consistent with traditionally gender norms, including the expression of intellectual abilities (Bem 1981; Steffens and Jelenec 2011). Others may integrate aspects of both masculine and feminine identification into their self-concept, termed androgyny.

The sex-role mediation hypothesis proposes that a masculine or androgynous sex-role identity promotes the development of spatial ability (Nash 1979). This theory proposes a number of mechanisms, including self-selection of play and leisure activities throughout childhood and adolescence, self-efficacy beliefs and motivation to practise tasks that encourage spatial competency, and sex-role conformity pressures (Reilly and Neumann 2013). This hypothesis has been tested a number of times over the decades, and two meta-analyses have been conducted (Reilly and Neumann 2013; Signorella and Jamison 1986). Both find support for sex-role mediation on the most prominently tested visual spatial task of mental rotation, but the scope of such reviews are limited by the shortage of studies testing other components of spatial ability. More recently an empirical study by Reilly, Neumann and Andrews (2016) tested support for the sex-role mediation hypothesis across a range of visual-spatial tasks, including mental rotation, spatial perception and spatial visualization. Masculine sex-role identification significantly predicted performance in both males and females.

10.3.5 Gender Stereotypes About Intelligence and Spatial Ability

Children begin to exhibit cultural stereotypes about what constitutes “masculine” or “feminine” by their early school years (Blakemore 2003; Ruble et al. 2006). This extends to characterising particular scholastic subjects and intellectual interests as masculine or feminine. For example, mathematics and geometry (which encourage development of spatial ability) is seen as masculine while language and arts are seen as feminine (Nosek et al. 2002). Boys also report greater interest and higher motivation in mathematics – a finding that is replicated cross-culturally (Goldman and Penner

2014). Such stereotypes influence the way that men and women see themselves in relation to intellectual domains generally (Nosek et al. 2002), as well as their motivation to persevere when they encounter obstacles to learning (Meece et al. 2006).

While gender stereotypes may influence interest and motivation, they also shape perceptions of our abilities and self-efficacy. Despite there being no scientific evidence for gender differences in general intelligence, parents typically believe their sons are more intelligent than daughters (Furnham 2000; Furnham and Akande 2004; Furnham et al. 2002; Furnham and Thomas 2004). These gender stereotypes are quickly incorporated into children's own self-beliefs and persist into adulthood. A consistent finding cross-culturally is that when asked to rate their own level of general intelligence, males tend to estimate their intelligence level considerably higher than do females (for a meta-analysis see Szymanowicz and Furnham 2011). The effect size of this gender difference is not insubstantial, $d = 0.34$. Males also rate themselves as more spatially competent than females, $d = 0.43$, which is again a moderately sized effect.

Popular cultural stereotypes (e.g. Pease and Pease 2001) that women can't read maps or navigate without asking for directions do women a real disservice. Males in general are seen as more capable at performing spatial tasks by a significant degree (Halpern et al. 2011; Lunneborg 1982), and gender stereotypes can become self-fulfilling prophecies that undermine both interest in such tasks as well as performance (Steele 1997). Recognizing that spatial ability is not immutable, but that it can improve with learning and instruction is an important first step for any targeted intervention aimed at eliminating the gender gap and ensuring gender equity.

10.3.6 Differential Practice of Spatial Skills by Boys and Girls

Piaget (1951) was one of the earliest scholars to suggest that play is an important part of child development, helping to develop childrens' motor skills and spatial abilities. Boys and girls are typically encouraged by parents to engage in stereotypically masculine and feminine play consistent with their gender (Eccles et al. 1990), but boys and girls also express preferences for different types of toys themselves (Hines 2015b). For example, boys tend to show a preference for vehicles and weapons while girls show more interest in dolls. The effect size for this gender difference is extremely large, with one study in children aged 4–10 years finding an effect size of $d = 2.0$ (Pasterski et al. 2005). While there is considerable gender segregation in the types of toys marketed to boys and girls (Blakemore and Centers 2005), it is difficult to separate how much these choices are culturally directed and how much of the preference is biologically based. Recall that early androgen exposure prenatally has been associated with male-typical toy and play preferences (Auyeung et al. 2009; Hines 2010), suggesting at least some influence on boys' and girls' choices. Indeed, this strong effect is even found amongst non-human primates divorced of human cultural traditions. Male primates express greater interest and play longer with stereotypically masculine toys such as balls, cars, and trucks while female primates preferred dolls and plush animals (Alexander and Hines 2002; Hassett et al. 2008).

Caplan and Caplan (1994) have argued that many stereotypically masculine toys and activities encourage the practice and development of spatial skills, while traditionally feminine play reinforces other culturally valued traits like communication and cooperation. For example, construction blocks and model assembly requires children to read 2D depictions of 3D objects and then find the correct spatial orientation of small and similar looking parts, while carpentry involves precise measurement of spatial relations and manipulation of parts. At earlier ages, toys like cars and trucks offer hands-on practice in visually tracking a moving object and judging the correct angle and speed to cause collisions. Girls play less on average with spatial toys than do males (Jirout and Newcombe 2015), and thus have less opportunities to practise these skills. Even if the effect of differential practice of spatial skills offers only a modest initial advantage to boys, the effect may grow larger as children enter adolescence and begin to self-select leisure activities and hobbies that they enjoy and are competent at performing. Activities such as carpentry, mechanics, models, and computer games would further enhance visual spatial skills.

There is strong evidence to support the theory that gender differences in spatial ability are at least partially influenced by differential levels of practice between boys and girls. Surveys and questionnaires measuring participation in spatial activities are positively correlated with performance on a range of spatial tests (Baenninger and Newcombe 1989; Chan 2007). However, it is equally plausible that people with high spatial ability may be the ones who want to engage in spatial activity in the first place (Baenninger and Newcombe 1989). It does seem likely that spatial activity experiences may be developmentally important in children (Doyle et al. 2012), and that differential levels of practice make some contribution.

10.4 Interventions for Training of Spatial Ability

A considerable body of evidence attests to the malleability of visuospatial reasoning, and that peak spatial ability is only reached with sufficient environmental input and experience (Baenninger and Newcombe 1995; Caplan and Caplan 1994). While biological and social factors may result in males starting with a modest initial advantage over females in spatial ability, it is important to remember that it is an acquired skill; people do not emerge *de novo* and become *Tetris* grand masters. There is an old joke that starts with the question “How do you get to Carnegie Hall?” – the punchline of course is “practice, practice, practice”. Like any other learned skill, if we receive training and do appropriate practice we can improve spatial abilities over time.

A large number of studies have examined the effects of brief training interventions to improve spatial ability. While there is wide variation in effectiveness, almost all such interventions show some improvement in spatial ability. With the large number of studies, training types, and choices of samples, the technique of meta-analysis can provide an objective quantitative assessment. But before turning to these reviews, theoretical issues need to be considered.

There are four important theoretical questions. First, does spatial training benefit all recipients equally, or are there differential rates of improvement for males and females? If spatial training was only effective in those who already have a moderate level of proficiency, its usefulness in addressing the gender gap would be limited. Second, do the effects of training transfer to all spatial tasks (thereby indicating an improvement in latent spatial ability), or only to tasks that are very similar or indeed identical to those used in training? Sims and Mayer (2002) have questioned whether the effect of spatial training might simply be the result of practice and familiarity, rather than genuine improvement in latent ability. For interventions to be genuinely useful, training effects must generalise to novel and unfamiliar spatial tasks. Third, do the improvements to spatial ability persist over time or are they short-lived? Fourth, do all types of training interventions work, or do characteristics such as the type and intensity of training matter?

Two meta-analyses have investigated the effect of brief spatial instruction and training interventions. The first, by Baenninger and Newcombe (1989) investigated the effects of training in studies that used a repeated measures design (i.e. subjects' initial performance on a spatial test is measured, a brief training intervention is offered, and then spatial performance is tested a second time). Their review included studies spanning a considerable range of years from the 1940s to the 1980s. They found that substantial improvements could be made to spatial ability after training, with an impressive effect size of $d = 0.70$ when tested on the same spatial measure that they were trained on, and a more modest effect size of $d = 0.49$ when more general spatial tasks were administered. This is an important distinction, because it shows that the effects of spatial training generalize well to other spatial tasks rather than being simply familiarity with the test content arising from repeated administration. The researchers also sought to test whether there was evidence of differential improvement between males and females, but found no significant gender differences. What the researchers did not address though is whether the improvements to spatial ability persist over time. Instead the authors considered the intensity of the training intervention, finding that multiple sessions over several weeks delivered meaningful improvement and that extremely brief or single session interventions showed less substantive benefits.

While the review by Baenninger and Newcombe (1989) makes an important contribution to the literature, a number of researchers have argued that changes in men and womens' roles over the past few decades should result in smaller gender difference over time (Caplan and Caplan 1994). When research becomes too dated, it raises the question of whether it remains applicable to current generations. More recently, Uttal et al. (2013b) conducted an extensive meta-analytic review of the empirical studies on spatial training from more recent years. Their meta-analysis also included a large number of unpublished studies (such as masters and PhD level theses). This is important because there might be a selection bias in the literature towards publishing only statistically significant findings while non-significant findings may be discarded, termed the file drawer effect in psychology (Ioannidis et al.

2014; Rosenthal 1979). A genuine test of the effectiveness of training interventions would also need to consider findings that might disconfirm the hypothesis.

Uttal et al. (2013b) considered a wide range of spatial training interventions, from explicit instruction and courses to playing video games and practising spatial tasks. The meta-analysis found that spatial training interventions were highly effective, with an overall effect size of $d = 0.47$ which is a medium-sized effect. Consistent with the earlier meta-analysis by Baenninger and Newcombe there was no evidence for differential improvement between males and females. Both genders gained the same benefits from training. Moderator analysis also showed no difference in the type of training being offered, with similarly sized effects across interventions that offered spatial learning courses, practice on spatial tasks or practice on video games. Adults also showed similar rates of improvements as adolescents, and though there was a slight tendency for interventions with children to have larger effect sizes, this trend did not reach statistical significance.

Another important research question about training interventions is whether the effects persist over time. Most studies that report the results of a spatial training intervention test subjects at the conclusion of the intervention, but a number of the studies evaluated in Uttal et al. (2013b) introduced a short delay of a few weeks and some tested subjects after as long as several months (Terlecki et al. 2011). If there were genuine and lasting improvements to latent spatial ability, we should see similarly sized effects of improvement between studies that tested performance immediately to those studies that included some latency. The meta-analysis found the effect of training to be durable, with no diminution of improvement for studies that introduced a delay before retesting.

To address the question of whether training interventions show generalisability to other types of spatial tasks, Uttal et al. (2013b) compared studies that used very similar measures of spatial performance to that covered in training with studies that employed substantially different types of spatial tasks. Importantly, the meta-analysis showed no difference between these two categories, providing evidence of transfer to novel tasks.

The research outlined above provides strong evidence that regardless of gender, spatial ability is highly malleable with instruction and training. Furthermore these effects do transfer to other types of spatial tasks and persist over time. Even brief interventions seem to have some effect, but more intensive training over multiple sessions yields the strongest benefits. Importantly the effects of training generalise across tasks, and improvements can be delivered for practically any age group from children to older adults.

10.4.1 Spatial Training and STEM Outcomes

While spatial ability is important for many occupations, the most compelling benefits of spatial training are in improving mathematical and science achievement in students. Longitudinal studies have provided compelling evidence of an association between spatial ability and proficiency in mathematics and science (Wai et al. 2010), but to date only a limited number of studies have investigated whether spatial training translates into tangible improvements in STEM achievement. Cheng and Mix (2014) conducted a randomized control trial of spatial training in a sample of 6- and 7-year old children, finding improvements in a test of basic calculation skills. A subsequent study by Krisztián et al. (2015) that taught spatial training with origami over a 10 week period in a sample of fifth and sixth grade students found similar improvements in computation skills over a control group. At present there are no spatial training studies that have measured science learning outcomes though in children, and none with adolescents in high school.

Amongst college-aged young adult samples, only two studies have investigated whether increasing spatial ability translates to improvements in mathematics and science learning. Sanchez (2012) conducted a randomized control trial that offered an intervention to target spatial ability, and found that the spatial group outperformed controls when tested on their learning from a short course on volcanoes and plate tectonics. In another study operating over a longer time period, Miller and Halpern (2013) recruited a sample of male and female first-year college students and randomly assigned them to either a control group or a spatial training condition (consisting of six 2-h spatial training sessions over a 6 week period). The gender gap in spatial ability narrowed somewhat after spatial training. In addition, the grades in student coursework were examined at the end of the year (up to 10 months after training ended). Compared to the control group, those receiving the intervention achieved higher grades in their physics coursework ($d=0.32$) but not in other classes like chemistry or calculus. The study also found significant correlations between students' spatial ability and course GPA in the following sophomore year for a number of STEM courses, including electricity and magnetism, biology, engineering, and differential equations. The conclusions of this study are limited though by the small sample size for the treatment group (14 women, 24 men) which resulted in a reduced statistical power.

10.5 Reducing Gender Differences by Promoting Spatial Ability in Children

With the link between spatial ability and development of mathematics and science skills, a number of prominent educational and gender researchers have argued for the importance of developing spatial competency ability as a foundation for proficiency in STEM subjects (Hyde and Lindberg 2007; Newcombe and Frick 2010; Wai et al. 2009). With competing interests in a crowded curriculum, teachers and principals might be understandably reluctant to allocate time for regular lessons on promoting spatial competency. However, the effect of even brief training interventions over several sessions has been found to be effective in reducing the gender gap in spatial ability (Uttal et al. 2013a). Since both males and females can improve

Table 10.1 Summary of children's play and leisure activities providing spatial experiences

		Specific spatial abilities				
Age category	Play and leisure activity	SP	MR	SV	ST	WF
Toy and play experiences for younger children	Construction blocks	●	●	●		
	'Action-oriented' toys such as cars and vehicles	●			●	
	Geometric shape toys	●		●		
	Throwing and catching ball games	●			●	
	Jigsaws	●	●	●		
	Art and drawing activities	●		●		
	Mazes and maps	●				●
Enrichment experiences for older children	'Transforming' toys appropriate to age	●	●	●		
	Advanced construction bricks such as Lego™	●	●	●		
	Model building	●	●	●		
	Origami	●	●	●		
	Computer games (action)	●		●	●	●
	Computer games (puzzle)	●	●	●		
	Computer games (construction)	●	●	●		
	Perceptual and motor skills training such as juggling	●		●	●	
	Organised sports	●			●	●

SP spatial perception, *MR* mental rotation, *SV* spatial visualiztion, *ST* spatiotemporal, *WF* wayfinding and navigation

their spatial reasoning substantially, it might be applied broadly to all students, which avoids the potentially stigmatizing effects of singling out females as a group for special interventions.

While explicit training would benefit older students such as those in high school or entering college, Newcombe and Frick (2010) advocate the importance of early education for spatial intelligence *before* the gender gap widens. One approach would be to integrate spatial learning with existing content in the STEM curriculum. In a report by the American National Research Council (2006), a range of practical strategies are outlined for engaging students to think spatially as part of mathematics and science classes. Rich multimedia can present complex scientific concepts visually, and many electronic textbooks offer data visualizations that are interactive rather than being static displays. For example, force and motion concepts are difficult to convey verbally or from a printed diagram. By showing the motion path of a physical object, a child can see the effects of physical phenomena.

Parents and caregivers might also gently encourage spatial learning outside of school by providing children with play and leisure activities (outlined in Table 10.1) that encourage spatial development through attention to spatial relationships (e.g., higher–lower; longer-shorter; wider-narrower). Games such as jigsaws, construction blocks, and board games provide contexts that facilitate spatial learning. Newcombe and Frick also note that everyday conversation can also be an opportunity for parents to highlight the spatial properties of objects through questions and gently introduce spatial language and concepts into the conversation (Ferrara et al. 2011). Indeed, many household experiences can be learning opportunities to demonstrate spatial concepts, such as measuring and transformation of solids and liquids when moving ingredients from one container to another during cooking, or imagining what shape will be made if we fold a sheet of paper diagonally. Educational toys that provide examples of geometric shapes can be a good way to extend spatial language further by learning the names of common objects such as triangles, squares, circles, and relationships before introducing more complex shapes and concepts (Newcombe and Frick 2010).

Children as young as 3 or 4 years of age can understand the concepts of maps and how they relate to the physical world if introduced at the right pace (Shusterman et al. 2008), while puzzles like mazes can offer further practice of spatial and navigational skills (Jirout and Newcombe 2014). In older children, enrichment activities like jigsaw puzzles and origami can also provide additional opportunities to encourage spatial development (Boakes 2009; Taylor and Hutton 2013), particularly when parents and educators engage children in active conversation and provide guided assistance. Art and drawing activities can also provide practice in spatial perception and visualization skills (Calabrese and Marucci 2006). Age-appropriate toy robots that children can change into vehicles and back provides practice in learning complex multi-step transformations like that involved with spatial visualization, while a wealth of literature has shown that construction blocks provide opportunities to practise spatial perception and transformation skills (Caldera et al. 1999; Jirout and Newcombe 2015; Stannard et al. 2001). They also provide practice in interpreting two and three-dimensional diagrams, and then translating these diagrams into physical steps.

Another promising enrichment activity that aids in practising spatial skills may be video games. Computer gaming has emerged as a popular leisure activity for children and can be an opportunity to practise spatial skills. While boys still report playing more computer games than girls, in recent years the gap has been diminishing (Terlecki et al. 2011). Additionally, the wider availability of gaming on mobile phones and tablets may see shifts in gender patterns of usage. Not every player will enjoy first-person shooters or fast action games, and game developers are increasingly embracing other genres to entice non-game players into the market. However, not all games are equal, and some games may have greater educational potential than others. In a review by Spence and Feng (2010) on the contribution of videogame play to spatial cognition, action-based games and maze/puzzle genres emerged as the most likely to affect spatial cognition as they provide repeated practice in spatial perception, mental rotation, and navigation tasks. Indeed, a number of studies have shown that even brief training with computer games may be effective as an intervention (as reviewed earlier).

Parental concerns over the use of videogames may need to be considered if they are to be recommended. Concerns over violence in some types of videogames or excessive amounts of time spent playing remain legitimate (Festl et al. 2013). However, when enjoyed in moderation with parental selection of content there is evidence that the benefits for spatial cognition outweigh the costs (Ferguson 2007;

Uttal et al. 2013a). Parents may also be more comfortable offering less violent and adversarial games to their children, such as the popular construction and building game *"Minecraft"* which is appealing to boys and girls equally and is already used by some educators (e.g. Short 2012). Spence and Feng propose that gaming might also be an opportunity to deliver more targeted educational interventions specifically developed with the goal of raising spatial abilities in a similar fashion to commercial brain-training products.

There is also a strong link between the development of motor skills and spatial reasoning (Frick et al. 2009; Richter et al. 2000). Neuroimaging studies show that regions of the brain associated with motor skills are activated when performing mental rotation tasks (Halari et al. 2006; Richter et al. 2000). Interventions that consist of motor skills training have been shown to enhance mental rotation performance in children (Blüchel et al. 2013). Newcombe and Frick (2010) advocate that educators and parents should provide young children plenty of time for free play and physical action with objects like balls to provide practice in motor skills. By association, this should transfer into positive benefits for spatial ability.

Sporting activity and organised sports might also offer opportunities to more specifically develop spatial ability. While individual families may differ, sons typically receive greater encouragement to pursue athleticism and organised sports than daughters (Leaper 2005), and greater media attention and funding is given to male professional sports stars (Gill and Kamphoff 2010). In contrast, girls have lower enrolment in organised sports and withdraw from sporting teams at a higher rate (Vilhjalmsson and Kristjansdottir 2003). But there is evidence that playing sports may help to develop spatial ability (Moreau et al. 2015). When children who play regular sport were compared to similar aged matches who did not, those who played sport performed better on tests of spatial performance (Notarnicola et al. 2014), with similar findings in young adults (Lord and Leonard 1997; Moreau et al. 2011). Motor coordination is a significant predictor of mental rotation ability even after controlling for the effect of gender (Pietsch and Jansen 2012), and two studies have found that learning and practising juggling skills increased mental rotation performance for both adults and children (Jansen et al. 2009, 2011). Encouragement of sports activity within the context of the educational system and by parents may help to lessen the gender gap in spatial ability, in addition to the non-cognitive benefits (Moreau et al. 2015).

10.6 Directions for Future Research

Most researchers now endorse biopsychosocial models of gender differences in spatial ability (Halpern et al. 2007) rather than considering exclusively biological or social causes, and the debate has shifted towards their relative contributions. Whereas once spatial ability was considered fixed and immutable, a considerable body of research has demonstrated that exposure to new spatial experiences throughout early childhood promotes growth in spatial proficiency. Furthermore, spatial training interventions can produce substantial benefits that potentially could translate to a reduction or even the elimination of the gender gap in mathematics and science achievement.

As reviewed earlier, only a limited number of spatial training studies have measured subsequent outcomes in science and mathematics achievement outcomes however. To date though, there have been no spatial training interventions that have followed children longitudinally to follow their progress, and only a single study by Miller and Halpern (2013) has tracked the progress of college-aged students for a prolonged length of time. Arguments for spatial training interventions would be strengthened by further studies monitoring student progress over longer time periods. It would also allow investigators to determine what types of spatial training and at what intervals, will best deliver changes in STEM-specific outcomes. While brief interventions may well yield long-term improvement, it is also possible that spatial training will require maintenance "booster" training at periodic intervals to deliver lasting educational improvements.

10.7 Summary and Conclusions

While individuals may differ, on average males score higher in tests of visual spatial ability. They also rate themselves as more spatially competent than females. Gender differences in spatial ability emerge from an early age. While clearly observable in children, the gender gap widens in adolescence and continues to grow into adulthood where it is quite large. Gender differences are found for a variety of categories of spatial tasks, but the largest and most actively studied is mental rotation, followed by spatial perception and then spatial visualization skills. There are a range of theoretical perspectives on why gender differences in spatial ability develop from biology to environmental causes, but one of the most frequently argued causes is differential levels of spatial learning and practice between males and females. This is supported by retrospective studies finding associations between childhood spatial experiences and spatial ability in adults.

Gender differences in spatial ability also precede the development of gender differences in mathematics and science, and longitudinal studies have found that early performance on spatial tasks can predict future performance in STEM, even many years later. There is also robust evidence demonstrating that spatial ability is not an immutable skill, and that even brief interventions can deliver impressively sized improvements. Such evidence makes a compelling argument for integrating spatial learning into early education, but parents can also provide additional learning opportunities for their children by engaging in spatial language, demonstrating spatial concepts within the home, and providing toys and games that encourage spatial practice. In older children, computer games can provide an opportunity to learn and practise spatial skills if they express an interest them, and organised sports has also been shown to improve spatial ability. The research supports the conclusion that concerted efforts by educators to address the gender gap in spatial ability in children and adolescents may translate into improvements in girls' and boys' mathematics and science achievement. However there is a need for longitudinal studies to determine which types of training and at what intervals will best support students in this regard, and the extent to which this reduces the gender gap for STEM outcomes.

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Chapter 11
Ranking and Predicting Results for Different Training Activities to Develop Spatial Abilities

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11.1 Introduction

The review indicates that spatial abilities do predict both entrance into STEM occupations and performance on STEM-related tasks in young (Wai et al. 2009). This author indicates that spatial ability contributes in a unique way to later creative and scholarly outcomes, especially in STEM domains.

Is worth noting that results of many psychological science studies related with spatial ability provide benefits to developing cognitive abilities and therefore improvements in academic and professional performance (Lubinski 2010; Shea et al. 2001). Lubinski (2010) believes that cultivating these skills is imperative for ensuring scientific innovation. “These students have exceptional and under-challenged potential, especially for engineering and technology [....] We could do a much better job of identifying these students and affording them better opportunities for developing their talents”.

The importance of spatial ability in educational pursuits and the world of work, with particular attention devoted to STEM (science, technology, engineering, and mathematics) domains is a fact that many studies have demonstrated. Incorporating spatial ability in talent identification procedures for advanced learning opportunities can aid to get the complex needs of an ever-growing technological world; furthermore, selecting students for advanced learning opportunities in STEM without considering spatial ability might be problematic, in terms of academic success.

The mentioned study of researcher David Lubinski and colleagues at Vanderbilt University (Shea et al. 2001), indicate the evidence that spatial ability predicts the development of new knowledge, and especially innovation in science, technology,

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engineering, and mathematics (STEM) domains, above and beyond more traditional measures of mathematical and verbal ability.

La Laguna University as a pioneer and innovating center offers several training programs for improving the spatial ability of students belonging to all degrees in every engineering field of higher education (Martin-Gutierrez et al. 2010; Contero et al. 2006; Martín-Dorta et al. 2008). These trainings aim to improve those spatial abilities in a short time (always less than 10 h) and until now they have been based in tools supported by several technologies or devices (smartphones, iPads, augmented reality, virtual reality, videogames, notebooks, etc.…). During training, orthographic normalized views from elements and pieces are used. We are not only looking for improvement of the student's spatial ability but for his motivation and satisfaction prompted by the job done as well. During the last few years, several experimental tests have been carried out for validating each one of these trainings (Martin-Gutierrez et al. 2010; Contero et al. 2006; Martín-Dorta et al. 2008), and actually they have been broadly implemented in the curriculum of the Graphic Design subjects at the start of the semester (Martin Gutierrez et al. 2011).

Development of spatial skills by engineering students is directly linked to future success in their professional work (Adánez and Velasco 2002; Miller 1996; Sorby 2009), and is critical for understanding the contents of engineering graphics subjects (Thai et al. 2002). This capability can be described as the ability to picture three-dimensional shapes in the mind's eye. Acquiring this ability can be done through an indirect process by means of Engineering Graphics subjects where students perform sketching tasks, create and read orthographic and axonometric projections (Alias et al. 2002).

Some studies demonstrate that spatial abilities can improve by means of specific training. These abilities, in engineering area, can improve with multimedia exercises, 3D software and other technologies used in graphic engineering (Sorby 2009; Rafi et al. 2005; Mohler 2001).

In this work, we present the results obtained by several groups of engineering students so each one of them have undertaken a different kind of training. All groups enjoyed significant difference in their spatial abilities and from this point onwards, we may establish a ranking of trainings and a prediction model for each one of them, so every students' level can be found according to the kind of training performed.

11.2 Theoretical Framework

There can be no doubt that spatial ability is one of the components of human intelligence as this is backed by countless lines of research (Guilford and Hoepfner 1971; Lohman 1996). There is not, however, any clear agreement on the sub-skills that this component is made up of. McGee (1979) distinguishes five components of spatial skills: Spatial Perception, Spatial Visualisation, Mental Rotation, Mental Relation and Spatial Orientation. Some of the most widely accepted theories are the paper by Lohman (1996) and the Meta-analysis conducted by Linn and Petersen (1985), which identifies three kinds of spatial skills: Spatial Perception that requires participants to locate the horizontal or the vertical in a stationary display while ignoring distracting information. Mental Rotation involves the ability to imagine how objects will appear when they are rotated in two or three-dimensional space. Spatial Visualisation refers to the ability to manipulate complex spatial information when several stages are needed to produce the correct solution. Researchers from the fields of psychology (Pellegrino et al. 1984) and geometry (Olkun 2003) simplify this classification into two components:

- Spatial Relation "The ability to imagine rotations of 2D and 3D objects as a whole body"
- Spatial Visualization "The ability to imagine rotations of objects or their parts in three spatial dimensions by folding and unfolding".

11.2.1 Measurement of Spatial Skills

There are a large number of tools available for measuring spatial abilities but using this latter classification, in this work we chose two tests, one for each of the main categories outlined above, to enable us to quantify the values of the spatial ability:

- Mental Rotation Test (MRT) for spatial relations (Vandenberg and Kuse 1978).
- Differential Aptitude Test – Spatial Relations Subset (DAT: SR) for spatial visualisation (Bennett et al. 2007).

11.2.2 Spatial Skills: An Overview

Differences in spatial skills between men and women have been studied in many studies, which suggest that men have the edge over women in mental rotation tasks (Linn and Petersen 1985; Stumpf and Eliot 1999; Voyer et al. 2000). On the other hand, some authors have suggested that these differences may be influenced by the different social status of the people concerned (Massa et al. 2005), or by environmental and socio-cultural aspects (Levine et al. 2005). Knowledge of the relation between the regular tasks that men and women carry out and spatial abilities would therefore be a good indicator. Some studies done along these lines (Feng et al. 2007) conclude that videogames may be a tool to improve these abilities.

Spatial skills can improve with specific training. The methodologies used may differ, depending on the area of application (pen and paper sketches, Isometric sketching, multi-media platforms, on-line platforms, video games, virtual reality, augmented reality, specific software, physical materials, etc.). Contents such as descriptive geometry, orthographic views, three-dimensional modelling, etc., have been used in engineering in order to improve the spatial abilities of students. Sorby

(1996) and Alias et al. (2002) used a traditional graphics course on sketching activities, orthographic projection, isometric drawing. S.E. Wiley (1990) concluded that 3D solid models and animation may help in developing visual perception abilities. Martin-Dorta et al. (2008), compare the effect of several different methodologies for improving spatial abilities. Dünser et al. (2006) conclude that augmented reality is a highly useful tool for training spatial abilities. Rafi et al. (2008) demonstrate the effect of virtual reality based training on improving the spatial abilities of men and women.

11.3 Trainings for Improving Spatial Ability

In this work, we analyse six different trainings. Didactic material and proper tools have been developed for planning and designing a training series of short courses where the spatial abilities needed by engineering students may be improved. The course's contents introduce the students into the basic knowledge for sketching systems (except those based on videogames).

11.3.1 General Description and Trainings' Programming

The training has 1 week duration and starts on Monday. The first action before undertaking training is providing the students belonging to each training group with the MRT and DAT-5:SR tests for measuring their levels of spatial ability. Later, each group performs the training proposed during 5 days. Every day, the series of exercises planned will be resolved in 2 h, except the last day which is dedicated to an evaluation of 1 h. All training end on Friday and have 9 h duration. The students rest on weekend so the following Monday they are provided with the MRT and DAT-5:SR tests once again for measuring their new levels of spatial ability and finding out the gain acquired.

For training the spatial ability, the activities proposed require performing spatial tasks mentally which are measured in the spatial tests (Puzzles, Figures' rotation, Block, Intersection, Blocks' rotation, Assemblies).

11.3.2 Trainings Based on Videogames

Two trainings were designed for developing spatial abilities through videogame's use. One of them was configured for being completed on a PC (21 students) meanwhile the other was set for performing it on a Nintendo DS games console (14 students). The training consists on playing according to plan the different modes of the 'Tetris' videogame available for both PC and Nintendo DS versions (Fig. 11.1). The

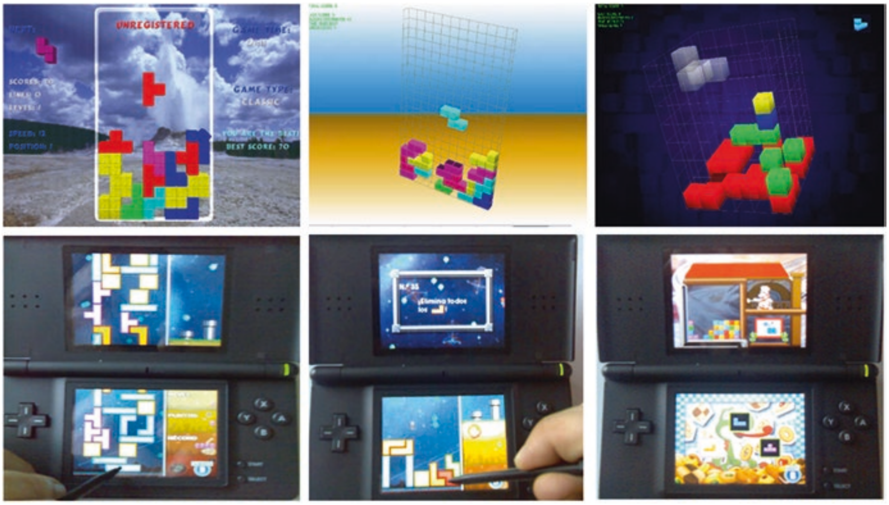

Fig. 11.1 Tetris videogame modes on PC y NDs platforms

training duration is 9 h. The choice of the videogame Tetris was conditioned for accomplishing the following requirements:

- It's a game that requires geometric figures and shapes.
- It allows performing operations of rotation and movement of figures.
- The spatial tasks that should be performed in the game will be related to both spatial ability components: spatial relations or spatial visualization
- The same videogame should have its own version on both platforms: PC and Nintendo DS.
- Possibility of using the tactile pen on Nintendo DS platform.

11.3.3 Training Based on Descriptive Geometry

The problem that the student usually finds while studying descriptive geometry's contents is facing static graphic sketches on paper or any web platform which don't offer the possibility of following the solution sequence in a 3D dynamic way.

The aim of descriptive geometry is transforming the 3D objects into 2D projections. For training based on descriptive geometry, we have developed a viewer, which allows performing the exercises' sequence in 3D being controlled and manipulated by the student. The 3D space may be rotated to any point of view with a simple movement from the mouse.

The viewer shows descriptive geometry (points, straights, planes, polyhedral figures…) and the solution sequence through the dihedral system's method. Besides, the projections of elements belonging to the projection planes are available for consultation.

Table 11.1 Contents of descriptive geometry training

1.	Introduction. Sketching systems
2.	Dihedral system. Point, straight and plane sketching
3.	Location of a straight line and point over the plane
4.	Intersection of planes and straight lines with other planes
5	Parallelism and perpendicularity
	5.1 Parallelism of straight lines
	5.2 Parallelism of a straight line and plane
	5.3 Parallelism of two planes
	5.4 Perpendicularity of a straight line and a plane
	5.5 Plane perpendicular to a straight line
	5.6 Perpendicularity of planes
	5.7 Perpendicularity of straight lines
6	Minimum distances
7	Polyhedrons
	Hexahedron projections. Study of three characteristics positions of a tetrahedron respecting the HP
	Tetrahedron projections. Study of three characteristics positions of a tetrahedron respecting the HP

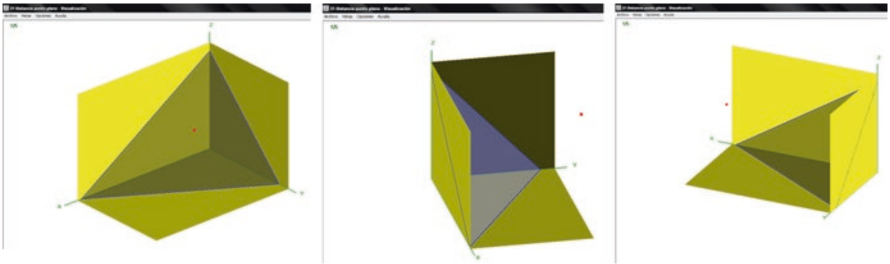

Fig. 11.2 3D Viewer based on OpenGL to show the Contents of descriptive geometry training

This fast course or training has been taught in two versions according to the methodology used. One version is based on master classes through blackboard explanations where 21 students attended (group DG) and another through master classes and computer viewer support, which provides the student with greater learning autonomy (group DG-3D). On both cases, the theoretical content is the same as a 65 pages book format.

The book fulfils a double condition: it's a manual for the students so they may be able to understand the basics of the dihedral system besides being a manual for those who have spatial vision difficulties but can develop it through spatial reasoning. The contents of the course are shown on Table 11.1 (Fig. 11.2).

11.3.4 Training Based on Hand Sketch Based Orthographic Views

Several authors have designed courses for developing spatial abilities of students through classic activities of Graphic Design (objects' sketching by normalized views/isometric perspectives) and sketching techniques (Sorby 2009; Sorby and Barartmans 1996). This strategy allows teacher to develop the student's spatial ability while introducing them to Graphic Design contents.

Following the same strategies that in previous courses, a printed exercise manual is designed containing a compilation of exercises about pieces in different categories according to difficulty levels for working over the sketching systems by orthographic views and perspectives. This course (Traditional Exercises –ET) or training has been performed by 29 students and its structure has five levels of growing difficulty where each level has several kinds of exercises for working on the sketching of objects through orthogonal views.

11.3.5 Training Based on Augmented Reality

The new generations of students pay more attention and are more interested in contents when teachers use CAD tools for performing exercises, multimedia material for explanations, web resources, virtual tutorship's, forum's communication… (everything related to Web 2.0) and show lesser motivation or even boredom at exercises performed with pen and paper through traditional graphic design tools (Wiley 1990).

The augmented reality application developed for this kind of training needs a book containing fiducially marks, which encode the 3D virtual models that the application contains. Over each page there are a couple of marks that encode the proposed exercise in that page. When the camera captures that marks, the AR system may sketch over a main mark the 3D model matching the exercise on that page.

The student can turn the mark with his hands and see the model from any point of view. In this training, a new variable is added consisting on mind and hands coordination for visualizing the desired point of view. The training/course have been performed by 24 students with a five levels structure and a duration of 2 h for each one, except level 5 (evaluation) where six exercises must be completed in just 1 h without any kind of help about the models (*knowledge*, *comprehension*, *application*, *analysis-synthesis*, *and evaluation*) (Fig. 11.3).

Fig. 11.3 Exercise sample with augmented reality

11.3.6 Control Group and Overall Student's Population

Freshmen students belonging to La Laguna University degrees compose each sample group. At the moment of performing this study, a control group has been taken into account, composed by 25 students from the overall population that have not undertaken any training.

11.4 Results and Ranking

In first place, we made sure that spatial abilities belonging to every group are analogue. Having that in mind, the ANOVA is carried out and the results obtained show that all groups have analogue MRT and DAT starting levels. Every training achieves an improvement of spatial ability although values vary accordingly. However, we consider certain limitations in this study due to huge standard deviations among groups as shown on results due to the lack of detection of significant differences between groups. Possibly groups may be different but our sample used is too small for causing that difference to become significant (Table 11.2).

For checking out if the improvement of training is significant, we use t-Student considering as null hypotheses H_0 the fact that average values of spatial ability don't vary when the course ends meaning that 'students who undertake the course don't develop their spatial abilities'. In every case, the result of comparing the average pre and post-test values through t-Student series in paired tests point out that the difference is significant, so it can be stated that courses have provided an improvement from the statistic point of view. For assessing the improvement values, a covariance analysis is performed (2-way ANCOVA). The ANCOVA method allows us to eliminate the difference of pre-test scores between groups and the adjusted post-test scores, revealing the real effects of the experimental treatment. So, it eliminates the possible memory effect. As a reference, the control group is taken with a pre/post

Table 11.2 Values Pre/Post Test and gain scores

	Pre- test		Post- test		Gain MRT	Gain DAT5:SR
*(SD) des. Std.	MRT	DAT5:SR	MRT	DAT5:SR		
Videogame PC n=21	20.76 (8.01)	37.76 (9.33)	27.48 (9.03)	45.46 (5.85)	6.72 (4.54)	7.70 (5.09)
Videogame NDS n=14	12.43 (5.73)	40.78 (6.37)	22.79 (9.19)	46.07 (5.34)	10.36 (4.76)	5.29 (3.76)
DG n=21	20.81 (7.40)	31.29 (10.41)	27.76 (8.81)	39.43 (9.36)	6.96 (6.68)	8.14 (5.32)
DG-3D n=19	17.32 (9.56)	29.53 (8.44)	26.42 (8.33)	38.53 (5.55)	9.11 (7.83)	9.00 (4.37)
AR n=24	19.67 (7.91)	29.17 (7.29)	27.71 (7.83)	38.46 (7.05)	8.04 (5.31)	9.29 (4.08)
ET n=29	19.79 (7.62)	28.48 (9.48)	28.76 (8.79)	37.10 (9.00)	8.97 (5.41)	8.62 (6.25)
Control Gr. n=25	17.44 (9.82)	28.40 (10.17)	22.08 (9.94)	33.52 (11.77)	4.64 (4.36)	5.12 (7.13)
Tot. population N=445	18.65 (8.35)	29.41 (9.18)				

test difference of zero points and it's adjusted to a new post-test value. This way, we may be able to compare the groups knowing the post-test adjusted value. This statistical procedure tested the interaction between training conditions (all groups). The dependent variables, co-variants and independent variables were post-test measurements, pre-test measurements and training condition respectively. The suitability this analysis' usage was tested by assessing the analysis through a statistical model containing interaction terms between the co-variants (pre-test mean scores of MRT and DAT-5:SR) and the independent variables for assessing the assumption of homogeneity between gradients.

11.4.1 ANCOVA Results for MRT and DAT-5:SR

The ANCOVA table breaks down the variability of post-test into contributions due to various factors. Since Type III sums of squares have been chosen, the contribution of each factor is measured after removing the effects of all other factors. According to the results of the Co-variance Analysis for Post-MRT, there is a statistical difference between the training courses and the control group, all p-value ≤ 0.05, thus there are differences in the levels of spatial abilities depending on the kind of training undertaken. Similar results were obtained for the Post-DAT-5:SR as there is statistical significance between the different kinds of training (all p-value ≤ 0.05) (Tables 11.3 and 11.4).

Table 11.3 Analysis of ANCOVA MRT

Source	Squares sum type III	Gl	Quadratic average value	F	Sig.
Corrected model	10,078.932(a)	8	1,259.866	43.033	0.000
Intersection	3,183.330	1	3,183.330	108.732	0.000
Pre_MRT	9,147.987	1	9,147.987	312.465	0.000
Course type	416.148	7	59.450	2.231	0.034
Error	5,240.558	179	29.277		
Total	144,496.000	188			
Total corrected	15,319.489	187			

Table 11.4 Analysis of ANCOVA DAT-5:SR

Source	Squares sum type III	Gl	Quadratic average value	F	Sig.
Corrected model	10,919.574(a)	8	1,364.947	65.769	0.000
Intersection	3,351.098	1	3,351.098	161.470	0.000
Pre_DAT-5:SR	7,446.425	1	7,446.425	358.800	0.000
Course type	375.025	7	53.575	2.581	0.015
Error	3,714.910	179	20.754		
Total	320,173.000	188			
Total corrected	14,634.484	187			

Table 11.5 Real gain MRT values for each training

Parameter	B	Typical error	T	Sig.	95 % confidence interval	
					Min. value	Max. value
Intersection	6.927	1.381	5.017	0.000	4.203	9.651
Pre_MRT	0.869	0.049	17.677	0.000	0.772	0.966
AR	3.694	1.550	2.383	0.018	0.635	6.753
ET	4.634	1.481	3.129	0.002	1.711	7.557
DG	2.754	1.610	1.711	0.089	–0.423	5.932
DG-3D	4.449	1.647	2.702	0.008	1.199	7.699
PC	2.510	1.610	1.559	0.121	–0.667	5.687
NDS	5.060	1.823	2.776	0.006	1.463	8.657
CONTROL	0(a)	.	.	.	.	.

11.4.2 Real Gain Values for MRT and DAT

The Tables 11.5 and 11.6 show the correction of the mean post-test value for each kind of course. Column B shows the value of the gain for all courses in comparison with the control group.

Table 11.6 Real gain of DAT-5:SR values for each training

Parameter	B	Typical error	T	Sig.	95 % confidence interval	
					Min. value	Max. value
Intersection	13.015	1.415	9.199	0.000	10.223	15.807
Pre_DAT5	0.722	0.038	18.942	0.000	0.647	0.797
AR	4.385	1.302	3.367	0.001	1.815	6.954
ET	3.524	1.243	2.834	0.005	1.070	5.977
DG	3.825	1.353	2.827	0.005	1.155	6.495
DG-3D	4.193	1.387	3.023	0.003	1.456	6.930
PC	4.768	1.395	3.418	0.001	2.016	7.521
NDS	3.609	1.592	2.266	0.025	0.467	6.751
CONTROL	0(a)	.	.	.	.	.

Table 11.7 Adjusted post-MRT average values

Course type	Average	Typical error	95 % confidence interval	
			Min. value	Max. value
AR	26.648(a)	1.106	24.466	28.831
ET	27.589(a)	1.007	25.602	29.576
DG	25.709(a)	1.186	23.368	28.050
DG-3D	27.404(a)	1.243	24.952	29.856
PC	25.465(a)	1.186	23.124	27.805
NDS	28.015(a)	1.476	25.102	30.928
CONTROL	22.955(a)	1.083	20.817	25.092

Table 11.8 Adjusted post-DAT-5:SR average values

Course type	Average	Typical error	95 % confidence interval	
			Min. value	Max. value
AR	41.142(a)	0.941	39.285	42.998
ET	40.280(a)	0.862	38.579	41.982
DG	40.582(a)	0.996	38.616	42.547
DG-3D	40.950(a)	1.053	38.872	43.028
PC	41.525(a)	1.011	39.529	43.521
NDS	40.366(a)	1.254	37.891	42.841
CONTROL	36.757(a)	0.927	34.927	38.586

11.4.3 Adjusted Average Values for Post-MRT and Post-DAT

The Tables 11.7 and 11.8 show the average values for MRT and DAT, obtained by each group after performing the training.

Table 11.9 Courses' ranking for improvement of spatial ability

Rank	Gain MRT		Rank	Gain DAT-5:SR	
1°	NDS	5.060	1°	PC	4.768
2°	ET	4.634	2°	AR	4.385
3°	DG-3D	4.449	3°	DG-3D	4.193
4°	AR	3.694	4°	DG	3.825
5°	DG	2.754	5°	NDS	3.609
6°	PC	2.510	6°	ET	3.524
CONTROL		0	CONTROL		0

11.5 Ranking and Prediction Models

The real gain values of each training, obtained from Tables 11.7 and 11.8 are arranged in Table 11.9 so all trainings are arranged in Table 11.9 so their ranking can be observed according to the gains obtained in the development of spatial ability.

We propose a mathematic model for predicting the result of post-test measurements for all trainings according to the student's pre-test spatial ability level. So, according to the MRT and DAT each student have, it's possible to find out which level may be reached later if he performs a certain course.

With the paired data of pre/post test scores belonging to each course, the adjustment of different curves by least-squares and is chosen the most suitable expression to the data known (linear, exponential, logarithmic, potential or polynomial). The coefficient of determination R2 identifies the curve's adjustment goodness of fit.

These adjustment models of the different curves for each course. The following adjustment models for each course's different curves (y = post-test; x = pre-test) are exposed with the most suitable choice shaded having in mind the correlation coefficient's value and the model's simplicity (Table 11.10).

From the prediction's point of view, the coefficient of determination shows the variability percent between the y variable (after test) that may be explained by the x variable (prior to test). A linear prediction model is proposed in every case because of the model's simplicity and similar magnitude to every other model according to the R2 adjustment (Table 11.11).

11.6 Conclusion

While starting the academic year, students are proposed several short courses for developing spatial abilities. In courses based on performance of sketching exercises with pen and paper format there is a risk of students quitting because of boredom, lack of motivation and unattractive tasks, that's why all contents and developing task should be supported by an attractive platform which may attract their attention while keeping them interested while following training.

Table 11.10 Predictive models to train with augmented reality

MRT_ RA		R2
Linear	$y = 0,7644x + 12,676$	0.60
Exponential	$y = 14.574e^{0.305x}$	0.59
Logarithmic	$y = 10.854\ln(x) - 3.4218$	0.55
Potential	$y = 7.2746x^{0.4512}$	0.59
Polynomial	$y = 0.0233x^3 - 0.6623x^2 + 8.0668x - 11.707$	0.63

DAT-5_ AR		R2
Linear	$y = 0.8107x + 14.812$	0.70
Exponential	$y = 19.587e^{0.0225x}$	0.70
Logarithmic	$y = 19.28\ln(x) - 25.868$	0.65
Potential	$y = 6.1273x^{0.5453}$	0.67
Polynomial	$y = 0.15x^2 - 3.13x + 44.59$	0.73

Table 11.11 Prediction models for different types of training

Course		Regression models
AR based	**MRT**	Post-MRT = 0.7644*Pre-MRT + 12.676
	DAT-5	Post-DAT = 0.8107*Pre-DAT + 14.812
Traditional exercise	**MRT**	Post-MRT = 0.9132* Pre-MRT + 10.684
	DAT-5	Post-DAT = 0.7333*Pre-DAT + 16.216
DG-3D	**MRT**	Post-MRT = 0.805*Pre-MRT + 11.593
	DAT	Post-DAT = 0.5835* Pre-DAT + 21.144
DG	**MRT**	Post-MRT = 0.8626* Pre-MRT + 10.581
	DAT	Post-DAT = 0.7736* Pre-DAT + 15.225
NDS	**MRT**	Post-MRT = 1.4395* Pre-MRT + 4.8947
	DAT	Post-DAT = 0.7348* Pre-DAT + 16.104
PC	**MRT**	Post-MRT = 0.9755* Pre-MRT + 7.2233
	DAT	Post-DAT = 0.5628* Pre-DAT + 23.796

Aiming that tasks do not become a routine so students lose interest on both training and the technology used, the training should be of short duration, with different kinds of exercises and many ways to use the toll so the students will not repeat the same kinds of exercises and consider that toll as repetitive. Dealing with it this way, the tool used for this training may favor the student's commitment to the course.

- The linear model is the most suitable choice for predicting the improvement of spatial abilities one individual may have, regardless of the training performed.
- The training with videogames is the strategy which most improves the spatial abilities, but doesn't contribute knowledge about Graphic Design content so they don't provide any learning to students.

- The training with augmented reality can be performed autonomously as material designed allows this possibility.
- The use of 3D tools improves attention and motivates student for working on Graphic Design contents.
- A short duration course of roughly 10 h, aimed to develop the spatial ability on engineering students provides a huge improvement on spatial vision's levels.

As a pending future work, the validation of these predictive models will take place. So, the spatial ability levels will be measured predicting the level achieved through certain training. Afterwards, that value will be compared to the one obtained once training is complete.

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Chapter 12
How Does Space Interact with Numbers?

Virginie Crollen and Marie-Pascale Noël

12.1 Introduction

Spatial abilities are important for educational pursuits, especially as regards the domains of science, technology, engineering and mathematics (STEM). For instance, Wai et al. (2009) showed a clear relation between visuo-spatial abilities assessed in 400,000 high school students and the probability of entering and succeeding 11 years later in disciplines related to STEM. In this study, spatial thinking was a better predictor of mathematics success than verbal skills. Nearly all those holding a science, technology, engineering or math PhDs were within the top 12 % on spatial ability 11 years earlier. Uttal and Cohen (2012) presented a very nice review of this association between visuo-spatial abilities and STEM disciplines considering in particular geology, medicine, chemistry and physics. According to these authors, spatial abilities predict STEM career choice as students who cannot think well spatially will have more trouble getting through the early, challenging courses that lead to dropout. However, spatial ability usually does not predict performance at the expert level. Indeed, expert's spatial knowledge is intimately embedded with their semantic knowledge of their domain of expertise and is thus quite different from the skills measured by spatial ability tests.

On that basis, Uttal and Cohen (2012) report the very interesting work of Sorby. Noticing that some freshmen students (mainly women) had poor spatial visualization abilities, Sheryl Sorby developed a 10-week course to improve the 3-D spatial skills. It included exercises of topological relations, projections and measurement. A pilot version of the course showed significant gains in a battery of spatial ability tests (Sorby and Baartmans 2000). In another study, Sorby (2009) tested this same program in middle school students (12–13 years old). Students who followed the

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training showed significant improvement in their spatial skills and girls who underwent the training went on to enroll in more follow-on math and science courses than did girls in a similarly identified comparison group.

In this chapter, we focus on mathematics as a subset of STEM subjects. This domain indeed requires visuo-spatial processing. This is obvious for geometry which is ostensibly spatial and requires creating, maintaining, and performing transformations on 2–D or 3–D visuospatial models. However, it is also the case for other mathematical dimensions. Understanding the place-value system of Arabic numbers for instance requires the processing of the position of each digit in the number. Doing multi-digit calculation in columns similarly involves the processing of spatial information; and the use of visual images has been shown to be positively correlated with higher mathematical word-problem-solving performance (Van Garderen 2006). Globally, numerous researchers have found close connection between spatial thinking and mathematics (Mix and Cheng 2012) at different ages, with good math abilities in people with higher spatial skills. For instance, preschoolers' performance on two tests of spatial-related ability (the reproduction of geometric designs and a spatial scanning task) was correlated with their strategy choices in addition (Geary and Burlingham-Dubree 1989). In adolescents, spatial-mechanical reasoning correlated with tests measuring fractions, number sense, measurement, geometry and data representation (Casey et al. 2001). Research also showed that spatial skills are a significant predictor of mathematics (Farmer et al. 2013). For instance, in adolescents mental rotation was shown to predict math aptitude (Casey et al. 1995).

Similarly, children with clearly impaired visuo-spatial abilities but intact verbal abilities, i.e., presenting a non-verbal learning disability (NVLD) (Mammarella and Cornoldi 2014; Nichelli and Venneri 1995; Rourke 1989) show a series of difficulties in mathematics. More particularly, these children perform significantly worse than typically developing children in numerical tasks where spatial reasoning is prevalent such as geometry (Mammarella et al. 2013) written calculation and number ordering (Mammarella et al. 2010; Venneri et al. 2003, see also Rourke and Conway 1997). Differences between NVLD and control children are particularly evident in Euclidean geometry and in geometrical transformations. Mammarella et al. (2010, 2013) moreover demonstrated that visuo-spatial working memory differences were able to account for group differences.

Thus, correlations between spatial skills and mathematics have been observed both in typically developing children and in children with NVLD. This relation is of course expected when we consider numerical tasks that have a high spatial component such as geometry, graph reading, …. However, recent research indicates that even very basic numerical processing involves a spatial dimension. This will be the main focus of our chapter. In the first part of this chapter, we will examine evidence showing that number magnitude is spatially coded (for reviews, see de Hevia et al. 2008; Fias and Fischer 2005; Gevers and Lammertyn 2005; Hubbard et al. 2005). Then, we will show that the spatial representation of numbers improves with age. Third, we will report the effects of weak visuo-spatial abilities on numerical development in children. Finally, we will consider how this space-number interaction has been considered in training aiming at fostering numerical development.

12.2 Evidence of the Interactions Between Number and Space in Healthy Participants

12.2.1 The SNARC Effect

As soon as 1880, Galton already reported that some people developed idiosyncrasic representations of numbers with each number occupying a distinct spatial location. These "number forms" could be colored, could present changes in luminosity in some locations or could occupy different planes. But, importantly, the number form of a given person was thought to show a clear intra-subject consistency by always presenting the same structure, each number always evoking the same visual pattern, involuntary and automatically (see Fig. 12.1). Since Galton, the existence of numbers forms has received direct empirical support from a wealth of experiments (e.g., Seron et al. 1992). About 15 % of normal adults were indeed reported to experience vivid visuo-spatial experiences of numbers (Seron et al. 1992).

However, beside those idiosyncratic representations of numbers that are consciously reported by some people, the major evidence used to support the fact that numbers and space interact with each other comes from an effect observed in response times: the Spatial-Numerical Association of Response Codes (SNARC) effect (Dehaene et al. 1993). In a typical SNARC task, the participant has to make a numerical discrimination, such as deciding whether a number is odd or even, by means of key presses. In some blocks the "odd" response is given by a left-hand key press and the "even" response by a right-hand key press. In other blocks, the mapping is reversed. The widely replicated result consists in better performance when participants respond to a small number with the left keypress and to a large number with the right keypress versus using the reverse mapping (see Wood et al. 2008, for a review). Importantly, because the SNARC effect was observed even when

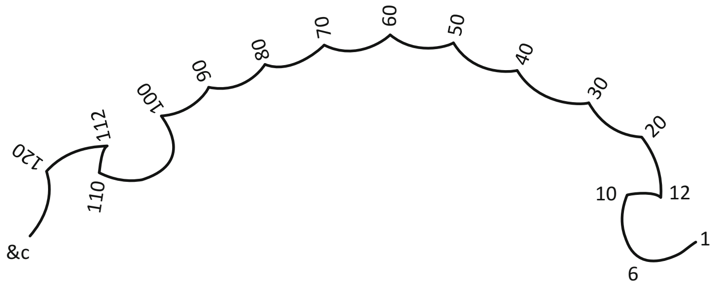

Fig. 12.1 Example of a number form (Reproduced from Galton (1880))

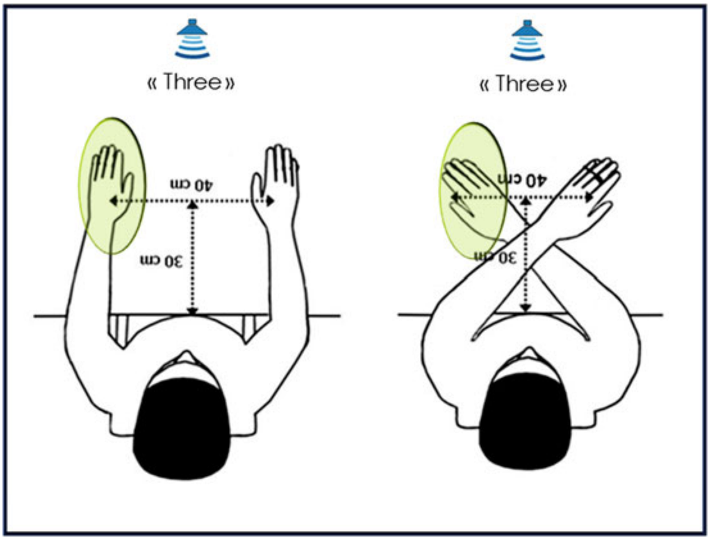

Fig. 12.2 SNARC effect in a parity judgment task. Small numbers (such as three) are responded to faster with the *left* keypress even if it's the *right* hand that is used to respond (in the crossed position)

participants crossed their hands (i.e., left/right hand in the right/left side of space), numbers were assumed to be mapped onto an external frame of reference (Dehaene et al. 1993; but see Wood et al. 2006), where small and large numbers facilitate responses in the left and right side of space irrespective of the hand of response (see Fig. 12.2). As we will see in the following sections of this chapter, the SNARC effect has been observed in a wide variety of tasks, is automatic and flexible and has received different explanations, each of them indexing a specific aspect of the connection that occurs between numbers and space.

12.2.1.1 Automaticity of the SNARC Effect

The SNARC effect has been observed in parity judgment tasks (Dehaene et al. 1993) but has also been reported in number comparison (i.e., decide whether a number is smaller or larger than 5; Dehaene et al. 1990) and in tasks requiring judgments of phonemic content of number words (i.e., determine whether an /e/phoneme was present in the name of a visually presented arabic digit; Fias et al. 1996). The SNARC effect has even been demonstrated in non-numerical tasks involving spatial judgments (i.e., discrimination of the orientation of a triangle or a line superimposed on a digit: Fias et al. 2001; Lammertyn et al. 2002), and in tasks involving goal-directed movements (Fischer 2003; Fischer et al. 2003, 2004; Schwarz and Keus 2004). In the well-known experiment of Fischer and collaborators (Fischer et al. 2003), participants had to react as quickly as possible to a target presented either in the left visual field (LVF) or in the right visual field (RVF) after a single digit number (1, 2, 8 or 9) had been presented as a fixation point. The detection of the LVF target was facilitated after the numbers 1 and 2 had been presented whereas the detection of the RVF target was facilitated after the digits 8 and 9 had been presented. A non-informative, completely task-irrelevant digit was therefore shown to influence shift of attention (Fischer et al. 2004; Schwarz and Keus 2004) or pointing movements (Fischer 2003; Fischer et al. 2003) towards lateralized targets. These results indicate that the allocation of attention is automatically influenced by the (irrelevant) number presented as the fixation point and that similar structures underlie attention shifts across internal spatial representations and external space.

The interactions between number and space do finally not need the presence of any overt or covert left/right responses (Nicholls et al. 2008) to occur. Numerical magnitude has indeed been found to modulate excitability of the early visual cortex, with smaller numbers increasing excitability of the right occipital areas (representing the left visual half-field), and larger numbers increasing excitability of the left occipital areas (representing the right visual half-field) (Cattaneo et al. 2009).

12.2.1.2 Flexibility of the SNARC Effect

Cultural and contextual factors were shown to influence the SNARC effect. Whereas European people, who write from left-to-right, show a classic SNARC effect, Arabic (Dehaene et al. 1993; Zebian 2005) or Hebrew (Kazandjian et al. 2010) speaking adults, who write from right-to-left, show a reversed SNARC effect. Furthermore, the context plays an important role. For instance, bilingual Russian-Hebrew readers showed a SNARC effect after reading Cyrillic script (from left-to-right), but they showed a reduced SNARC effect after reading Hebrew script (from right-to-left) (Shaki and Fischer 2008). In the same way, while the spatial-numerical association is oriented from left-to-right in participants asked to imagine the numbers positioned on a ruler, it is oriented from right-to-left in participants asked to classify numbers as hours of the day coming before or after 6 o’clock (Bächtold et al. 1998; Vuilleumier et al. 2004). The digits 4 and 5 also elicited faster left than right responses when the digits ranged from 4 to 9, but elicited faster right than left responses when digits ranged from 0 to 5, indicating that the SNARC effect is driven by the relative instead of the absolute magnitude of the number (Ben Nathan et al. 2009; Dehaene et al. 1993; Fias et al. 1996).

12.2.1.3 Development of the SNARC Effect

The onset of the SNARC effect is not clear (Patro and Haman 2012). A SNARC effect was indeed described in 7-year old children when explicit processing of numerical magnitude was required (in a magnitude comparison task) and in 8–9-year old children when the numerical information was not explicitly processed (see also, Imbo et al. 2012, for Belgium children; van Galen and Reitsma 2008, for

Dutch children). However, a SNARC-like effect was found in 8–9 month-old infants (Bulf et al. 2015) and in preschoolers during a non-symbolic numerosity comparison task (Patro and Haman 2012). It was indeed recently demonstrated that perceiving numerosities causes lateralized shifts of visual attention in 8–9 months infants. Infants were faster at detecting targets appearing on the right when cued by large numbers, and targets appearing on the left when cued by small numbers. Preschoolers' reaction times in a non-symbolic numerosity comparison task were moreover faster when small sets were presented on the left side of the screen and when large sets were presented on the right side of the screen. These findings in preliterate infants suggest that left-to-right number ordering may have some sources that are independent of reading and math education. Patro et al. (2016) finally demonstrated that the number–space link can be quickly constructed in preschool children's on the basis of spatially oriented visuo-motor activities. The authors trained 3- and 4-year-old children with a non-numerical spatial movement task (left-to-right or right-to-left), where via touch screen children had to move a frog across a pond. After the training, children had to perform a numerosity comparison task. After left-to-right training, a SNARC-like effect was observed, while a reverse effect was observed after right-to left training. These results suggest a causal link between visuo-motor activities and number–space associations. Manual games might indeed shape number–space associations in children before the acquisition of writing and reading.

12.2.1.4 Theoretical Models Accounting for the SNARC Effect

The SNARC effect was first interpreted as an index of the spatial organization of the magnitude representation of numbers, the mental number line. According to this mental number line model, the representation of numbers is isomorphic to the representation of physical lines and presents three major features. Firstly, numbers are represented on the mental number line by equal distributions of activation. Therefore, the larger the distance between the quantities being compared, the more distant their distributions of activation on the mental number line and the easier it is to discriminate between them (i.e., distance effect; Dehaene 1992, 1997, 2001, 2003). Secondly, the mental number line is logarithmically scaled, so that small numerical magnitudes are further apart on the number line than large numerical magnitudes. This leads to less accurate representation and poorer discrimination of large than of small numbers i.e., size effect; Aschcraft and Battaglia 1978; Buckley and Gillman 1974; Moyer and Landauer 1967). More interestingly for our purposes and based on these observations of the SNARC effect, the mental number line is assumed to be spatially oriented from left to right (see Fig. 12.3). Within this framework, small numbers are responded to faster with left-sided responses and large numbers are responded to faster with right sided-responses because this stimulus-response association is congruent with the left-to-right orientation of the mental number line (at least in people from Western societies). This interpretation has been referred to as

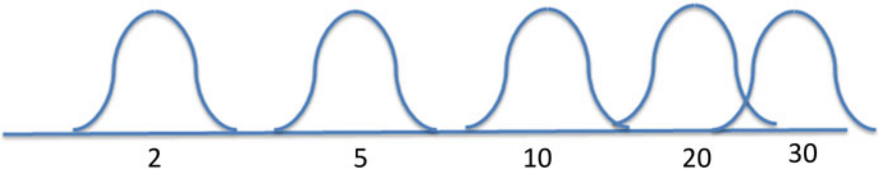

Fig. 12.3 Representation of the mental number line and of its three majors features: (1) constant and Gaussian activation curves across numbers; (2) logarithmic compression; (3) *left-to-right* orientation

the "*visuo-spatial coding account*" (Gevers et al. 2010) but other accounts have also been proposed.

T*he polarity coding* account, for instance, argues that stimuli and responses are represented at an intermediate level as negative (−) or positive (+) polarity (Proctor and Cho 2006). Within this framework, small numbers are coded as – polarity and large numbers are coded as + polarity. Left responses are similarly coded as – polarity while right responses are coded as + polarity. Because corresponding polarities cause faster response selection, small numbers will be responded to faster with the left keypress and large numbers will be responded to faster with the right keypress.

In the same line, *the verbal-spatial account* proposed by Gevers et al. (2006) supposes that a "categorization layer" exists between the numerical representation and the production of the responses. The function of this middle layer is to categorize numbers as small or large, odd or even or any given category that is required by the task. The model moreover assumes that two different routes map the numerical representation and the response stage. On the one hand, the automatic route is triggered in any numerical context and accounts for the fact that a digit (i.e., small or large) automatically primes a particular response (left or right). On the other hand, the controlled route is activated intentionally by the participants in accordance with the task's instructions (e.g., small numbers → left hands). If the two routes converge on the same response, responses will be faster than if they do not converge. In this last case, the response primed by the automatic route must be deprogrammed before the correct response can be initiated, thus explaining by itself the occurrence of the SNARC effect (see also Notebaert et al. 2006; Santens and Gevers 2008). According to this account, the dimensional overlap between number and response location in the SNARC effect is thus not necessarily located at a visuo-spatial level but might also be situated at a categorical level, i.e. at a level of spatial representation that is not analogous to physical space but that is tightly linked to language (Gevers et al. 2006, 2010; Proctor and Cho 2006; Santens and Gevers 2008).

The idea that visuo-spatial and verbal-spatial information can be engaged differently in different tasks has finally been proposed in the literature. As the SNARC effect disappears under spatial load in magnitude comparison tasks (Herrera et al. 2008; van Dijck et al. 2009) while it disappears under verbal load in parity judgment tasks (van Dijck et al. 2009), it was assumed to primarily originate from visuo-spatial associations in magnitude comparison tasks while it was assumed to primarily arise from verbal associations in parity judgment tasks.

More recently however, another proposition has been made explaining the SNARC effect by a coding of *order information in working memory*. Indeed, as the association between number and space is very flexible, van Dijck and Fias (2011) argued that it is probably not linked to long-term memory but created in short-term memory. To sustain their hypothesis, they developed a research paradigm in which number order in short-term memory was manipulated independently of number magnitude (Fias et al. 2011; van Dijck and Fias 2011). More precisely, participants were asked to memorize a sequence of numbers. Afterwards, they had to perform a parity judgment but only on the numbers that belonged to the memorized sequence. The authors demonstrated that left-sided responses were faster for numbers presented at the beginning of the sequence (regardless of their magnitude) while right-sided responses were faster for numbers presented at the end of the sequence (see also van Dijck et al. 2014 for similar results when participants performed a speeded dot detection task with dots appearing left or right, while maintaining digits or letters in working memory). The activation of the standard sequence of numbers (e.g., from 1 to 9) can therefore be overruled when a new random sequence is memorized. However, this is only observed when retrieval of the memorized sequence is required during the numbers classification task (Ginsburg et al. 2014). In contrast to the visuo-spatial coding account, this last model therefore supposes that the association between numbers and space is built online to facilitate task execution and that it is the ordinal position of the numbers that is spatially coded in working memory.

12.2.2 Number Bisection

Another stream of evidence supporting that numbers and space interact with each other come from the number bisection task, the numerical counterpart of the line bisection task (Calabria and Rossetti 2005; Fischer 2001). The line bisection task has been widely used to investigate spatial attention and requires participants to bisect a line into two parts of equal length by marking its subjective midpoint with a pencil. Normal right-handed people tend to systematically bisect lines slightly to the left of the objective midline (leftward bias or pseudoneglect effect; see Jewell and McCourt 2000). This leftward bias has been interpreted as reflecting the dominant role of the right hemisphere in attentional control. According to this view, the pseudo-neglect effect is therefore due to the fact that the right hemisphere bias attention to the left visual space so that lines appear longer in the contro-lateral left hemifield. Interestingly, several studies provided evidence that similar spatial bias occurred in the numerical domain (Priftis et al. 2006; Vuilleumier et al. 2004; Zorzi et al. 2002). Accordingly, when control participants are required to indicate (without calculating) the number midway between two others presented auditorily or as Arabic digits, (i.e., number bisection task), they tend to respond with numbers smaller than the true midpoint (Cattaneo et al. 2011a; Longo and Lourenco 2007, 2010). This underestimation bias is accentuated when participants perform hand movements in their left peripersonal space (irrespective of the hand used) whereas it decreases when participants perform movements in their right peripersonal space (Cattaneo et al. 2011b). These findings indicate that proprioceptive cues related to the moving hand attracted attention to the side of the hand movements and hence to the corresponding end of the mental number line, modulating the pre-existing directional bias (Cattaneo et al. 2011b).

12.2.3 Arithmetic Operations

The intrinsic connection between numbers and space has also been found in tasks involving arithmetic problems solving (Masson and Pesenti 2014; McCrink et al. 2007). In their preliminary study, McCrink and colleagues (2007) showed adults videos of events involving addition or subtraction of items and required them to judge whether or not different final numerosities were the correct outcome of the operation. Overall, participants appeared to accept as correct a well-defined range of plausible answers, depending on the arithmetic operation that had to be carried out. Although the responses to small problems tended to be centered on the true outcome, as problem size increased, they tended to be biased in the direction of larger numbers for addition and of smaller numbers for subtraction. According to McCrink et al. (2007), the so-called operational momentum effect is consistent with the view that numerical operations involve movements on a spatial mental number line (Dehaene and Cohen 1991; Gallistel and Gelman 1992; Hubbard et al. 2005; Restle 1970): as small numbers are represented on the left of this continuum and large numbers on the right, addition problems involve a rightward displacement while subtraction problems yield a leftward displacement. Systematic biases were observed to a lesser extent with Arabic numerals (Knops et al. 2009) and in a task requiring speeded pointing to arithmetic results (Pinhas and Fisher 2008). In this task, symbolic addition and subtraction problems were presented to participants who were required to compute the result of the operation before locating it on a visually presented number line. Consistently with the previous experiments, pointing was biased leftward after a subtraction problem and rightward after an addition problem. McCrink and Wynn (2004, 2009) finally presented videos of rectangles being added or subtracted from one another to 9-month-old infants. In the addition condition, four rectangles were serially added to a set of six rectangles. In the subtraction condition, 4 rectangles were serially removed from a set of 14 rectangles. Then, 3 different outcomes were presented to the children: an incorrect outcome of 5 items, a correct outcome of 10 items and an incorrect outcome of 20 items. Interestingly, infants' looking times were significantly longer when the outcome presented violated the momentum of the arithmetic operation (i.e., outcome numerically larger in the subtraction condition and outcome numerically smaller in the addition condition). To conclude, the operational momentum hypothesis assumes that under- and over-estimation are observed because participants are moving too far on their mental number line while performing approximate arithmetic operations. In other words, under- and overestimation are observed because participants shift their locus of attention along the number line in the direction of the operation (toward larger numbers for addition and toward smaller numbers for subtraction).

In a more recent study, Masson and Pesenti (2014) demonstrated that arithmetic operations induced some spatial shifts of attention. In their study, they asked their participants to perform a target detection task following arithmetic problems solving (arithmetic facts and complex arithmetic problems). They showed that additions improved the target detection to the right side of the screen while subtraction improved the target detection to the left side of the screen. Masson and Pesenti (2015) also demonstrated that participants are slower to solve subtractions when distractors are located on the left while they are slower to solve addition when distractors are located on the right. Altogether, these data not only confirmed the idea that attentional shifts underlie mental arithmetic but also demonstrated that attention shifts may disturb the solving of arithmetic problems.

12.3 Improvement of the Numerical Representation

Several pieces of evidence suggest that the acquisition of numerical symbols provides access to a more accurate representation of numbers. The first data supporting this idea probably date back several years when Buckley and Gilman (1974) demonstrated that the distance and size effects were smaller in tasks involving symbolic numbers than in tasks involving non-symbolic quantities. It was therefore assumed that the representation of numerical symbols was less approximate (less compressed) than the representation of non-symbolic quantities. Moreover, in a more recent study, no significant correlations were found between the symbolic and the non-symbolic distance effects (calculated on the basis of reaction times), this lack of correlation suggesting that symbolic and non-symbolic numerical quantities may be processed by different underlying representations (Holloway and Ansari 2009).

While both symbolic (De Smedt et al. 2009; Holloway and Ansari 2009) and non-symbolic (Gilmore et al. 2010; Halberda et al. 2008) arithmetic abilities were shown to be in a close relationship with mathematical achievement, only the lack of symbolic numerical representations (in animals and in some indigenous human cultures) appeared to preclude the development of higher mathematical skills (Dehaene et al. 2008; Gallistel and Gelman 2000; Gordon 2004; Pica et al. 2004). For instance, whereas speakers of Mundurukú, an Amazonian language with a very small lexicon of number words, were able to add, subtract and compare approximate representations of large numbers far beyond their naming range, they were unable to solve exact arithmetic problems comprising numbers larger than 4 or 5. These data therefore suggest that the acquisition of numerical symbols plays a special role in the emergence of accurate numerical competence during child development.

A developmental transition from logarithmic to linear numerical representation has moreover been documented in several studies suggesting that children's representation of numbers changes over time with increasing experience with number symbols (Berteletti et al. 2010, 2012; Booth and Siegler 2006; Siegler and Booth

2004; Siegler and Opfer 2003). In these studies, children and adults had to place different numbers on a visual number line with 0 at 1 end and either 10, 20 (Berteletti et al. 2010), 100 (Siegler and Booth 2004) or 1000 (Booth and Siegler 2006; Siegler and Opfer 2003) at the other end (the number-to-position task). All these studies reported consistent results: the youngest children positioned numbers logarithmically when the experimental condition was unfamiliar (e.g., 1000) but positioned them linearly when the experimental condition was familiar (e.g., 100). In contrast, older children and adults positioned numbers linearly in both experimental conditions. The dissociation between familiar and unfamiliar conditions therefore reveals that children's performance changes with age and shifts from a logarithmic to a linear representation first for small known numbers and then progressively to large numbers. Interestingly, the linearity of the numerical representation appeared to be correlated to mathematical achievement (Booth and Siegler 2008; Siegler and Booth 2004).

According to Gunderson et al. (2012) this development of a linear representation of numbers might be a key factor, which could account for the great impact of spatial skills on numerical abilities. Results of two longitudinal studies support this view. First, children's spatial skills measured at the beginning of the first or second school year (through a mental rotation test) predicted their precision of number positioning on a 0–1000 line at the end of the school year (even when controlling for their level of precision of the number positioning, reading and math abilities at the beginning of the school year). Second, number line knowledge (on a 0–100 line, measured at age 6) mediates the relation between spatial skills (measured at age 5) and approximate symbolic calculation (measured at age 8). These results are consistent with the hypothesis that spatial skill can improve children's development of numerical knowledge by helping them to acquire a linear spatial representation of numbers. Based on this view, several training or remediation programs of number skills have included a component of spatial mapping between numbers and space (see point 5).

Interestingly, a linear model of number estimation seems to be related with a spatial–numerical association (Opfer and Furlong 2011; Opfer et al. 2010). In this study, the spatial-numerical association was tested in preschoolers by showing that they easily and accurately encoded the location of hidden objects when numbered from left-to-right but experienced tremendous difficulty when the same objects were numbered right-to-left (Opfer and Furlong 2011). Importantly, the preschoolers who were showing this spatial-numerical association displayed more mature, linear representations of symbolic value than age-matched preschoolers lacking spatial-numeric associations (Opfer et al. 2010).

The most prominent theory explaining the log-to-linear shift holds that children possess multiple mental representations of number: they initially rely on logarithmic number representation. Then, with age and experience, they become able to rely on more accurate linear representations (Booth and Siegler 2006, 2008; Laski and Siegler 2007; Opfer and Siegler 2007; Siegler and Booth 2004; Siegler and Opfer 2003). However, it is still not clear whether children experience a real log-to-linear shift of the magnitude representation or whether they increase their knowledge of the mapping that occurs between the magnitude representation and an external spatial medium. It has for example been proposed that a proportion-judgment account provides a better explanation than does the idea of a logarithmic-to-linear representational shift (Barth and Paladino 2011).

12.4 Interactions Between Number Representation and Space in Children Presenting Developmental Disabilities

Given the above-reviewed data on the interactions between number and space, some research investigated the possible impact of weak visual-spatial skills on the development of number magnitude representation. In a recent study, Crollen and Noël (2015) for example investigated whether developmental visuospatial weaknesses in children may also affect basic numerical tasks tapping the spatial aspects of number magnitude. Based on their performance on two design copying tests and a visuospatial questionnaire, fourth-grade children with low or high visuospatial skills were selected. Both groups of children were then asked to perform three numerical tasks (the number-to-position, the number bisection, and the numerical comparison tasks to measure a SNARC effect). Children from the low visuospatial group presented the classic SNARC effect but showed in every task larger deviation errors as compared to the high visuospatial group. These results therefore demonstrated that low visuospatial abilities did not change the nature of the mental number line but rather led to a decrease in its precision.

In a second study, Crollen et al. (2015) used the same design in children presenting a non-verbal learning disability (NVLD). They demonstrated that NVLD not only affected the number-to-position task that requires both the processing of number magnitude and the mapping between this magnitude and a spatial medium but also affected two tasks that tagged number magnitude but did not involve a physical spatial medium: the number bisection and the numerical comparison tasks. In both tasks, performance of children with NVLD witnesses a less precise number magnitude representation. A similar conclusion has been reached by Gomez et al. 2015 using number magnitude comparison tasks of Arabic digits or dot sets. In addition to this, Crollen et al. (2015) failed to observe any SNARC effect in NVLD children in the crossed as well as in the uncrossed hand positions (see also Bachot et al. 2005). NVLD could therefore lead to a number magnitude representation that would be less precise and that would present a disturbed spatial orientation or a less salient left-to-right orientation.

One may also wonder whether spatial difficulties could account for dyscalculia, a specific learning disability of mathematics. Dominant theories of dyscalculia suggest that it originates from the impairment of the approximate number system (Landerl et al. 2004; Piazza et al. 2010), or from impaired connections between number symbols and the approximate representation of numbers (Rousselle and

Noël 2007; De Smedt and Gilmore 2011). Recently however, Szucs et al. (2013) demonstrated that the dominant features of dyscalculia were impairments of visuo-spatial short-term and working memory and of inhibitory function. At least one neuro-imaging study could provide supporting evidence to this idea. Rotzer et al. (2009) indeed demonstrated that children with dyscalculia not only showed impaired working memory proficiency but also showed weaker neural activation compared to a control group during a spatial working memory task in the right intraparietal sulcus (IPS), the right insula and the right inferior frontal lobe. Furthermore, number-to-space mapping deficits have recently been shown to be associated with dyscalculia in children (Kaufmann et al. 2013) and in adults (e.g., Ashkenazi et al. 2009; Defever et al. 2014; Huber et al. 2015; Rubinsten and Henik 2005).

Altogether, the above-reviewed studies suggest that the mathematical difficulties that are encountered by NVLD and dyscalculic children could actually derive from a visuo-spatial working memory deficit (for NVLD, see Alloway 2007; Alloway and Archibald 2008; Mammarella et al. 2010; Venneri et al. 2003; for DD, see Huber et al. 2015; Rotzer et al. 2009; Szucs et al. 2013) which could prevent the formation of the left-to-right oriented mental number line (Bachot et al. 2005; Crollen et al. 2015).

12.5 Considering Space in Numerical Training

Based on this space-number association, some studies first question the possibility of enhancing numerical development through training of spatial skills, especially as enhancing spatial abilities is possible (see the meta-analysis of Uttal et al. 2013). Based on this idea, Cheng and Mix (2014) gave a 40 min training session of mental rotation to half of a group of 6–8 years old children. Only the children from the trained group improved their performance on mental rotation as well as on a calculation test, mostly for missing term problems (e.g., 2+ _ = 8). However, Hawes et al. (2015) failed to replicate this effect although they tested children of the same age and used a more intensive training (15–20 min three times a week for 6 weeks). They observed a significant impact of the training on measures of mental rotation but no effect on calculation, even on those with missing terms. To our knowledge, no other studies reported data supporting this way of impacting numerical development.

However, more numerous studies developed training or remediation programs that foster numerical development through the use of a spatial mapping of numbers. One of these first attempts was done by Ramani and Siegler (2008) who developed a linear number-board game to promote the numerical development of young children. Low-income children were invited to spend four 20-min sessions either playing a number or a color board game. Both consisted of a race, in which the child had to move a token from the left to the right of ten horizontally arranged colored squares. The steps were determined by a spinner that indicated either the number of moves to make (1 or 2) or a color to reach. In the number game, a number from 1 to

10 was written on each of the colored squares and the children had to read the numbers out loud as they moved their token (e.g., a child on Square 3 who spun a 2 should say “four, five” as he/she moved the token). In the color game, nothing was written on the colored squares and the child who spun a “blue” had to move the token to the next blue square by saying the intervening colors (e.g., “red, blue”) out loud. The results showed that the children who played the number board game improved their performance on a series of numerical tasks. More specifically, they improved significantly in identifying the name of Arabic digits (from 1 to 10), in comparing the magnitude of two Arabic digits (from 1 to 9), in counting (from 1 to 10), and in increasing their precision when asked to estimate the location of a given number on a line (marked 0 and 10 at the extremities). The difference in performance between the two groups was still significant 9 weeks later, indicating that the improvement was stable over time. Interestingly, the authors also assessed game playing at home. The frequency of playing with number board games was positively correlated with performance in the four numerical tasks mentioned above, while the frequency of playing card and video games was not. Encouraging these types of games in preschool thus seems to be fundamental. However, this study only shows the importance of playing a number game rather than a color game. In this respect, the second study of Siegler and Ramani (2009) was more interesting as they contrasted two number board games: one linear with numbers going from left to right as in the study reported here above, the other being circular with the numbers arranged on an a analog clock (with numbers increasing clockwise or counterclockwise). Two groups of low-income preschoolers played one of these games for a few sessions corresponding to about 1 h as a whole. It appeared that playing the linear number board game led to considerably greater learning than playing the circular game. This was particularly obvious for tasks measuring number magnitude, numerical magnitude comparison and number positioning on a line. Furthermore, children playing the linear board game learned more easily from a subsequent training on arithmetic problems. Thus, a linear left-to-right mapping of numbers seems particularly beneficial.

Fisher et al. (2011) compared two trainings in preschoolers (using a cross-over design). Each lasted for three sessions of 10–15 min. Both used the same numerical items and processes but one of them involved space and body movement, the other not. Indeed, in the control condition, children were presented with pairs of Arabic digits or collections, on a tablet PC, one on the top of the other and were asked to tick the larger. There was thus no systematic spatial-numerical correspondence. By contrast, in the experimental condition, children were standing on the middle field of a dance mat projected onto the floor directly in front of them. Children had to compare the magnitude of a presented number/dot set to that of a simultaneously presented standard. The standard was presented together with its position on a number line oriented left to right with extremities marked with 0 on the one hand and 10 or 20 on the other hand. Children had to compare the two magnitudes by taking a step to the left for probes smaller and a step to the right for probes larger than the standard. Results showed better benefit after the experimental training including the spatial mapping than the control one in two tasks: number positioning on a 0–10 line and verbal counting.

Using number-space mapping also seems to be very important for arithmetic's. Indeed, Booth and Siegler (2008) teached first-grade children four difficult problems (9 + 18, 26 + 27, 17 + 29, 49 + 43). In the experimental condition, spatial magnitude representations of the addends and of the sum were presented to the child while solving the problem (i.e., showing number line bars representing 38 and 48 when solving 36 + 48) or produced by the child him/herself. They found that children learn more easily the solutions of the problems when the computer presented the real spatial representations of the addends and the sum than when the child himself/herself tried to represent them (no feedback provided), when both the child and the computer showed these spatial representations or when no spatial representation was used.

With older children, Kucian et al. (2011) developed the "Rescue Calcularis" game in which children had to estimate the position of a number, the result of an addition or the result of a subtraction, on a 0–100 number line. When the estimation was within a range of ±10 of the correct position, the exact position was given as feedback. Both control and DD children (around 9 years old.) played this game about 25 times for 15 min within a 5-week period. Playing this game significantly increased children's spatial representation of numbers as well as their ability to correctly solve arithmetical problems. This was true for children of both groups. But the specificity of that study was to assess brain activation in these children before and after the training. In the scanner, children were presented with three Arabic digits and had to decide whether or not they were presented in order (ascending or descending). Before training, activation of fronto-parietal areas was revealed in both groups. Yet, relative to controls, DD children showed stronger activation in the frontal areas and weaker activation in the parietal areas (including the intraparietal sulci). Training led to a decrease of the fronto-parietal activations. This decrease of activation was stronger in the DD group and was interpreted as indicating that less attentional effort was needed to deal with the task. However, no control condition was used in this study.

Vilette et al. (2010) developed a very similar tool that they called the *Estimator*. The aim of this computer game was to develop the connection between exact and approximate number representations in addition and subtraction situations. Specifically, a horizontal line marked 0 at its left and 100 at its right extremity appears on the computer screen. A mark for 50, for each step of 25, each step of 10, or each unit can also appear on the number line (depending on the choice of the educator). Then, an arithmetic operation (an addition or a subtraction) appears (e.g., 12 + 23 = ?). The child was asked to read the problem aloud, and then, using the cursor, had to indicate the approximate position of the answer on the number line. If this approximation was correct (given a specified degree of accuracy, e.g., ± 5 or ± 1), the result of the calculation appeared on the computer screen and the next trial started. If the estimate was incorrect, the number corresponding to the position of the cursor on the number line appeared on the screen and the child was invited to propose another answer. This continued until a correct answer was provided. Ten children with a mean age of 10–11 played this game for seven sessions of 30 min each. Ten other children played, for the same amount of time, other computer games that used the same arithmetical operations, but focused only on exact solving procedures. Both groups were delayed by more than 2 years in their mathematical ability, compared to normally developing children. Significant improvements were evident for both groups after the intervention, but the *Estimator* group ended up with better performance than the control group in exact calculation, addition, subtraction and overall on the math battery which again speaks in favor of using spatial mapping in number learning.

Altogether, these studies argue in favor of the importance of using spatial representation of number magnitude on a left-right linear medium to develop the understanding of number magnitude but also to develop arithmetic abilities.

12.6 Conclusions

Observations made with healthy participants clearly demonstrate the existence of interactions between numbers and space. These interactions appear in very basic numerical tasks such as number bisection and arithmetic problem solving. But the most striking evidence of this association is probably the SNARC effect, a preferential association between small numbers and left-sided space and between large numbers and right-sided space. The recurrent observation of this effect led to the assumption that numbers are represented on a left-to-right oriented mental number line. Although the mental number line hypothesis is a well-known model to account for the various number-space interactions, alternative models such as the verbal-spatial model (Gevers et al. 2006, 2010) or the *working memory account* (Fias et al. 2011; van Dijck and Fias 2011) have been proposed in the literature.

Given the interactions that occur between numbers and space, visuo-spatial weaknesses have moreover been shown to affect numerical processing. Indeed, children with NVLD show a mental number line characterized by a lower precision and a lower saliency of its left-to-right orientation. Possibly the atypical development of visuo-spatial working memory in NVLD children (as well as in developmental dyscalculia children) could be a key factor in accounting for these difficulties. Further research should examine whether improving the visuo-spatial working memory in those children through training would have a positive impact on their specific mathematics difficulties. This issue is extremely timely since methods in mathematics education have received considerable interest in the past few years. This is probably because training studies can not only contribute to increase our theoretical knowledge on the development of numerical concepts but can also constitute the starting point for elaborating programs that assist children with difficulties or prevent mathematics difficulties in children at risk. This is particularly important as it has already been demonstrated that poor mathematical skills are associated with employment difficulties (Parsons and Bynner 1997; Rivera-Batiz 1992). As the spatial representation of numbers probably represents the cognitive underpinnings of abstract mathematical concepts that make them meaningful, it is worth examining the way to improve it.

Finally, as visuo-spatial abilities predict future achievement in science, technology, engineering, and mathematics (STEM) occupations (Sorby et al. 2014), it could be interesting to modify education services in order to develop more thoroughly spatial capacities (Andersen 2014). A recent study already demonstrated that spatial skills' training has a positive impact on middle school girls. Those who underwent the spatial skills training indeed went on to enroll in more follow-on math and science courses than did girls in a control group (Sorby 2009). However, as spatial abilities can be recruited in effective or ineffective ways depending on alignments between the demands of a task and the approaches individuals adopt for completing that task (Hinze et al. 2013), future studies should try to identify ecologically representative conditions for which spatial skills might be used effectively (Barron and Rose 2013; Hinze et al. 2013).

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