

## **Spatial Skills Literature Overview**

### *Introduction*

The possession of and ability to use well-developed spatial skills have long been acknowledged as critical to success in engineering studies<sup>1</sup> and practice. An engineer needs to be able to develop a mental picture of an object and “see” how it looks from different perspectives in order to determine relationships between it and another object. She also needs to be able to project how one can travel successfully from point to point. These skills are important in efforts to create and realize deliverables throughout the design process, from initial design to product specifications to prototype to finished item. Therefore, the development of spatial skills and subsequent appropriate and effective use of them are important research topics in engineering education.

Another reason for conducting research in this domain is to provide support for the recruitment and retention of female undergraduates in certain engineering disciplines. Facility with these skills is vital to success in disciplines in which female students are grossly underrepresented – and, not incidentally, the disciplines in which the great majority of undergraduate engineering degrees are awarded: civil engineering, electrical and computer engineering, mechanical engineering, and computer science (within engineering). In Academic Year 2008, females earned only 8.5% of the bachelor degrees awarded in these majors, which account for 66% of all bachelor’s degrees in engineering overall (Gibbons, 2010).

Common wisdom is that acquiring and using these skills have also long been acknowledged as easier, in general, for males than females. However, investigation into the roots of this “wisdom” indicates that certain types of activities, such as those that rely on hand-eye coordination, are important to skill development. It’s just that males are more likely than females to participate in those activities. Females given the same opportunities find that their spatial skills improve! To support this learning, it’s important to know how to assess a student’s level of spatial skills and have access to appropriate remediation information and activities. A primary goal, then, of this overview is to identify helpful resources to support these tasks.

The following topics are covered in this overview:

- Concise Review of the Literature
  - Definition of spatial skills
  - Factors affecting the development and exercise of spatial skills
  - Spatial skills as predictors of success in engineering
- Implications for Practice
  - Methods for assessing spatial ability skill levels
  - Review of educational initiatives and interventions
  - Implications and recommendations for practitioners
- Current and Future Research Areas

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<sup>1</sup> For a historical perspective see, for example, Findley (1951).

## Concise Review of the Literature

### *Definition of Spatial Skills*

Sorby (1999) discusses the difference between “spatial abilities” and “spatial skills.” Technically, the former refers to innate abilities and the latter to learned abilities; however, the two terms are often used interchangeably. We’ll use the term “spatial skills” in this overview to emphasize the point that these skills can be learned.

“Spatial skills” refer to, in general, a collection of cognitive, perceptual, and visualization skills. While lists may differ, substantial agreement exists that the core spatial skills are (Sutton & Williams, 2008; 115):

- the ability to visualize mental rotation of objects
- the ability to understand how objects appear in different positions
- the ability to conceptualize how objects relate to each other in space
- three-dimensional (3D) understanding

The traditional focus in research on spatial skills was on the understanding and manipulation of 2D space as well as 3D (*cf.* Olkun, 2003 and Sorby, 1999). Advances in computer architecture, processor speed and applications during the past several decades, however, meant that 3D design software became more and more accessible to students; therefore, the focus was more and more on the understanding and manipulation of 3D spaces. This shift in research focus resulted in minimal, if any, attention paid to the need to expose students to 2D images and issues. We recommend that attention be focused as well on 2D spaces and representations. Tests evaluate skills with respect to 2D as well as 3D representations, and 3D skills build on 2D ones (*cf.* Sutton, Heathcote, & Bore, 2005).

In a classic secondary study, Linn and Petersen (1985) established specific descriptions of gender differences in spatial skills. This study defines spatial skills as “skill in representing, transforming, generating, and recalling symbolic, nonlinguistic information” (1481). To facilitate their analysis, Linn and Petersen identify four research threads within which the majority of studies on spatial skills had been conducted: differential, in which spatial skills were compared among various populations; psychometric, in which factors affecting skills are identified through comparison of performance on a given set of tasks; cognitive, in which the universal process supporting (non)performance on a specific task or skill is determined; and strategic, in which solution strategies are the focus of the research. These four threads guide their review of experimental literature on spatial skills, resulting in the identification of the following three main categories of spatial skills:

- Mental rotation  
Determining the new projection of a 2D or 3D object that has been rotated from a certain position; see Figure 1, below.
- Spatial perception  
Determining relationships among objects with respect to space, size, and position; see Figure 2, below. The first test item has the subject marking a rectangle on a test form

to make it look like the rectangle that is projected before him/her. The subject must determine the number of blocks touching the marked ones in the second item. (Risucci, 2002; 292)

- Spatial visualization

Manipulating information sequentially and spatially; see Figure 3, below. In a test of spatial relations, a subject must determine the direction in which the first object was rotated and then apply the same rotation to another object. A spatial manipulation test has the subject create a 3D object from a 2D representation and then identifying the new location of indicated spots. A subject must identify a cross-sectional slice of a 3D object in the visual penetration test. (Titus & Horsman, 2009; 243)

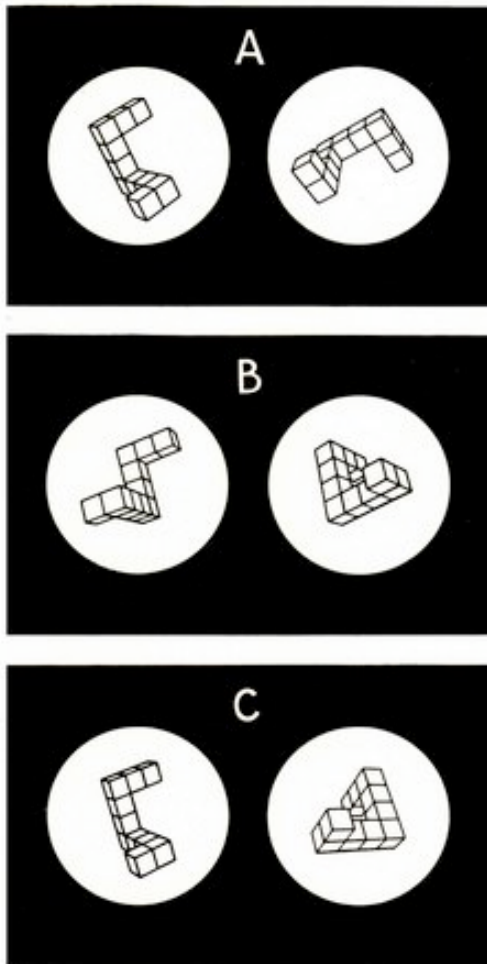


Figure 1. Examples of objects used in mental rotation tests (Shepard & Metzler, 1971; 702)

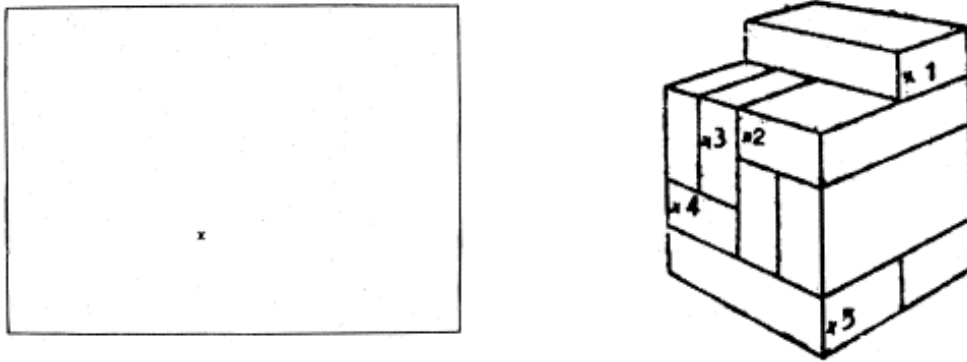


Figure 2. Two items testing visual spatial perception from the Cognitive Laterality Battery (Risucci, 2002; 292)

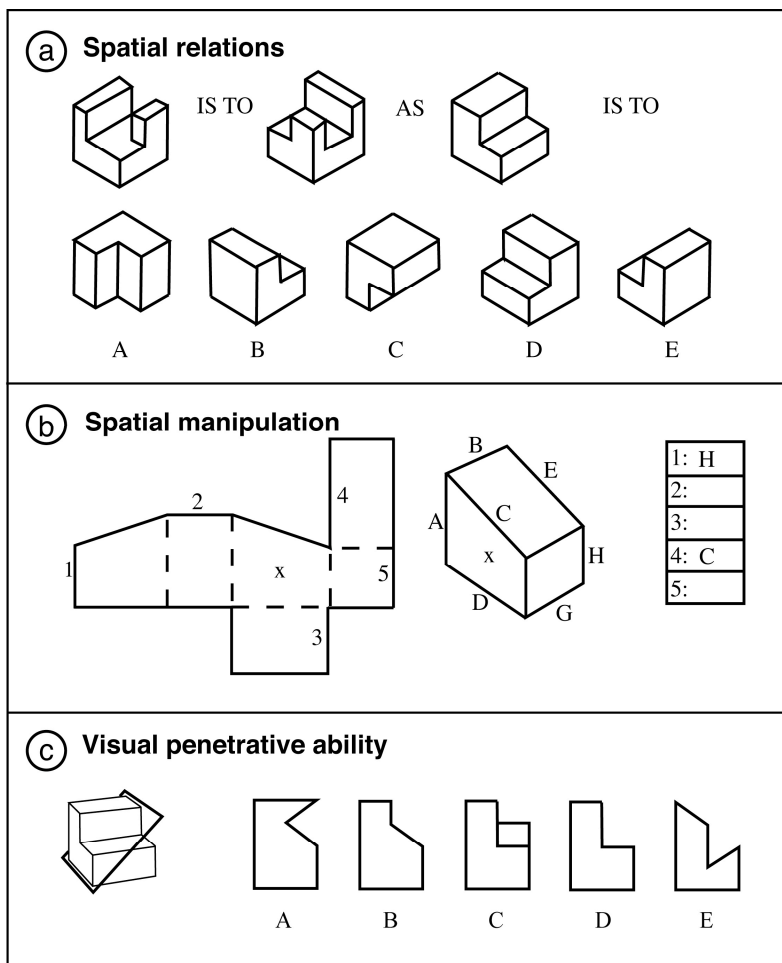


Figure 3. Spatial visualization test items (Titus & Horsman, 2009; 243)

Maier (1998) expands upon the work of Linn and Petersen (1985), identifying five main “elements” of spatial skills:

- Mental rotation

## Spatial Skills: Concise Review of the Literature

- Spatial perception
- Spatial orientation  
Orienting oneself physically or mentally in horizontal and vertical space
- Spatial relations  
Identifying and understanding the horizontal and vertical orientation and resulting relationships among objects or parts thereof
- Spatial visualization  
Picturing an image in which internal alterations are occurring

Maier's definitions of spatial orientation and relations are a refinement of Linn and Petersen's spatial perception category. His definition of spatial perception refers to the ability to locate along horizontal and vertical axes in the presence of distracting information or "noise."

Martín-Dorta, Saorín, and Contero (2008; 508) provide the following definitions of these skill categories:

Based on Linn and Petersen (1985) -

*Spatial Perception:* the ability to determine spatial relationships with respect to the orientation of one's own body, in spite of distracting information.

*Spatial Visualization:* the ability to manipulate complex spatial information when several stages are needed to produce the correct solution.

*Mental Rotation:* the ability to rotate, in imagination, quickly and accurately two- or three-dimensional figures.

Simplified from three categories to two based on work of other researchers -

*Spatial relations:* the ability to imagine rotations of 2D and 3D objects as a whole body (this includes mental rotation and spatial perception).

*Spatial Visualization:* the ability to imagine rotations of objects or their parts in 3D spatial by folding and unfolding.

The concept of multiple intelligences, developed by Howard Gardner, includes spatial intelligence; it is defined as the "(a)bility to orient and manipulate three-dimensional space." (Moran, Kornhaber, & Gardner 2006; 26) This robust concept of multiple intelligences is an important consideration in instructional design for several reasons, not the least of which is the reminder that we can't address spatial skill issues in isolation. We should consider other related intelligences, such as body-kinesthetic ("[a]bility to coordinate physical movement") and logical-mathematical ("[a]bility to understand and use logic and numerical symbols and operations"), when evaluating skills. (definitions from Moran, Kornhaber, & Gardner 2006; 26) Limitations on a person's body-kinesthetic intelligence, for example, may have a spillover effect on his/her abilities to exercise his/her spatial skills effectively.

### *Factors Affecting the Development and Exercise of Spatial Skills*

Research on factors that affect the development and exercise of spatial skills has traditionally focused on gender differences in performance. Recent research efforts, however, indicates that other factors, such as socioeconomic status and working memory capacity, may be involved. Research identifying these other factors affecting skill levels further indicates that an underlying factor may be the level of access to and use of objects and activities shown to improve spatial abilities such as video games (*cf.* Feng, Spence & Pratt, 2007 and Sorby & Veurink, 2010) and Legos (*cf.* Sorby, 2007): objects and activities which males are more likely to use than females. Sorby (2007) mentions that pre-college participation in activities relying on hand-eye coordination tends to be high among postsecondary students with good to excellent spatial skills, including certain sports and technical education/industrial arts classes – again, activities that males are more likely to participate in than females.

Levine, *et al.* (2005) note that socioeconomic status may affect the development of spatial skills. However, they also note that males tend to outperform females with respect to spatial skills because males are more likely to participate more in activities to develop those skills, such as video games. Internalized gender stereotypes and expectations, therefore, likely determine interest and socioeconomic status likely determines access to these activities. Because conditioning may be difficult to overcome, females may need additional encouragement and ongoing support from a trusted source to feel comfortable participating in activities society tends to label “guys only.”

Kaufman (2007) investigates the role of working memory in demonstrated differences in the performance of males and females on 3D mental rotation and spatial visualization tests. A secondary goal of his study is to identify the memory types or characteristics leading to gender differences in performance. Multiple tests of spatial working memory and spatial skills were administered to 50 males and 50 females who are high school juniors and seniors in Cambridge, England. Spatial working memory capacity is found to be the main factor in performance differences between the genders on spatial visualization (Differential Aptitude Test – Spatial Relations Subset, or DAT-SR) and, to a lesser extent, 3D mental rotation (Mental Rotation Test, or MRT) tests. Additionally, spatial short-term memory is found to be more predictive of female performance on spatial ability tests than males.

Finally, a person’s performance on a task may be compromised if the requirements go against stereotype or s/he belongs to a group about which negative performance expectations exist according to stereotype threat theory. McGlone and Aronson (2006) find that female undergraduates who receive reminders about their identity as a student at a selective private college before taking the Vandenberg MRT did better than females who are reminded about their gender only or a test-irrelevant identity. The results are reversed for the male students in the study. A primary conclusion of this study is that both genders are aware of the stereotypes surrounding performance on tests of spatial ability, but have different reactions to reminders. These results are verified in Moe (2009). The finding reported in Voyer, Voyer, and Bryden (1995) that gender differences in performance start appearing by age 13 and increase with age suggests that the longer a person has to internalize stereotypes regarding gender differences in

spatial skills the more impact the stereotypes have on performance. Singletary, et al. (2009) is the ARP resource suite on stereotype threat.

One positive result from a variety of sources is that the gender gap in performance on spatial visualization tests is closing, especially after training; however, the performance gap on mental rotation tests, especially with respect to 3D objects, persists. See, for example, Immekus and Maller (2010); Sutton, Williams, and McBride (2009); and Contero, et al. (2006).

### *Spatial Skills as Predictors of Success in Engineering*

Studies also indicate that the addition of spatial skills to traditional predictors for success in engineering studies – most notably, math and verbal skills as measured by standardized tests – leads to more robust results in identifying students who are more likely to succeed in undergraduate engineering studies, and who would benefit from remedial activities. Humphreys, Lubinski, and Yao (1993) report success in predicting membership in various educational and occupational groups by considering spatial-math and verbal-math abilities in their longitudinal study of 400,000 high school students. Webb, Lubinski, and Benbow (2007) find that considering spatial abilities along with SAT math scores in talent searches resulted in an enlarged pool of students with the potential for succeeding in math and science studies. Predictions of performance in undergraduate engineering design courses are enhanced when a composite score of spatial abilities, willingness to use intuition, and math grades is used instead of reliance on math scores alone (Field, 2007).

### Implications for Practitioners

Practitioners need to be able to assess spatial skill levels using appropriate instruments and identify and implement appropriate interventions in order to encourage the development and/or enhancement of spatial skills effectively. The tests most mentioned in recent research, and therefore, presumably, the most used in skills assessment, are the DAT-SR, Mental Cutting Test (MCT), and (V)MRT. See, for example, Contero, et al. (2006); Martín-Dorta, Saorín, and Contero (2008); and Németh (2007).

#### *Methods for Assessing Spatial Skills*

The following list of tests is adapted from Sjölander, 1998 (pp. 50 – 51).

#### *Mental Rotation Tests*

Test Name	Description	Primary Reference
Spatial Relations subset of the Primary Mental Abilities Test (PMA-SR)	Mental rotation of 2D objects	Thurstone & Thurstone (1949)
Cards Rotation Test (CRT)	Mental rotation of 2D objects	Ekstrom, et al. (1976)
Mental Rotation Test ([V]MRT)	Mental rotation of 3D objects	Vandenberg & Kuse (1978)
Generic Mental Rotation Tasks (GMRT)	Variant of the Shepard and Metzler (1971) chronometric task	Voyer, Voyer, & Bryden (1995)
Rotation of Images	Matching images	Dureman & Sälde (1959)
Left or Right Hand Identification	Identify pictures of RH or LH images	Dureman & Sälde (1959)

#### *Spatial Perception Tests*

Rod and Frame Test (RFT)	Adjust a rod under distracting conditions	Witkin & Asch (1948)
Water Level Test (WLT)	Indicate orientation of liquid in a tilted container	Piaget & Inhelder (1956)

## Spatial Skills: Implications for Practitioners

### *Spatial Visualization Tests*

Paper Form Board (PFB)	Decide which shapes can be made out of a set of fragmented parts	Likert & Quasha (1941)
DAT-SR	Indicate what an unfolded shape will look like when folded a certain way	Bennett, Seashore, & Wesman (1947)
Identical Blocks Test (IBT)	Identify a block from a list that is the same as a standard based on a variety of cues	Stafford (1961)
Block Design subset of various Wechsler intelligence scales	Reconstruct a shape using 3D blocks	Wechsler (1946 – 1981)
Paper Folding (PF)	Identify the unfolded piece of paper that is the same as a folded version	Ekstrom, et al. (1976)
Embedded Figures Tests (EFT and CEFT)	Find a simple figure embedded within a complex pattern	Witkin (1950)
Hidden Figures Test (HFT)	Find a simple figure embedded within a complex pattern	Ekstrom, et al. (1976)

Other tests include:

- Mental Cutting Test (MCT; see, for example, Hartman, et al., 2006)  
Determine the shape of a “slice” cut from a 3D object on a plane; see Figure 3(c), above
- Objective Test on Orthographic Projection (OTO) and related tests the Descriptive Test on Orthographic Projection and Descriptive Test on Perspective Projection (DTO and DTP; see, for example, Takeyama, et al., 1999)  
For the OTO, determine the correct orthographic projection from an isometric drawing; for the DTO, be able to draw various lines, planes, and geometric objects based on written directions; and for the DTP, be able to apply shades and shadows based on written directions
- Purdue Spatial Visualization Test (PSVT; see, for example, Bodner and Guay, 1997)  
See Figure 3, above
- Space Imagination Test (see, for example, Górska and Juščáková, 2003)  
Determine various spatial relationships among lines, planes, and geometric objects; reassemble a geometric object from a set of pieces

Voyer, Voyer, and Bryden (1995) provide a discussion regarding the efficacy of various assessment methods. They report that, with respect to gender performance, the CRT, GMRT, PFB, and PMA-SR provide significant results; the DAT-SR and PF provide homogeneous but

not significant results; the RFT and Wechsler's Block Design provide results that are significant for some but not other age groups; and that the results of the MRT, WLT, IBT, and EFT are affected by scoring and testing influences. This information can be used to guide the selection of appropriate assessments.

Eliot and Smith (1983) is another reference with an extensive discussion of tests and assessment methods; they cover thirteen categories of tests, including copying and maze, visual memory, surface development, and collage tasks.

### *Initiatives and Interventions*

There is ample evidence that spatial skills can be improved through training. The finding of trainability holds even for the skill for which the largest performance gender gap exists, mental rotation. Training tools, methodologies, and curricula are covered in the following reports:

- Contero, et al. (2006)  
Description of and presentation of research results on the efficacy of learning support tools eREFER and eCIGRO, developed in response to the implementation of the Bologna Declaration in 1999, in the development of spatial visualization, freehand sketching, and normalized view generation skills
- Ferguson, et al. (2008)  
The use of handheld mechanical dissection manipulatives by students during lectures and exercises leads to increased scores on the PSVT: Rotations test
- Hsi, Linn, and Bell (1997)  
Instruction in successful solution strategies to spatial reasoning problems leads to an overall increase in performance, with gender differences in performance on the generation of orthographic projections eliminated on post-test
- Martín-Dorta, Saorín, and Contero (2008)
- Onyanha, Derov, and Kinsey (2009)
- Onyanha, Towle, and Kinsey (2007)
- Sorby and Baartmans (2000)
- Sorby, *et al.* (2006)  
Gaining/reinforcing expertise in 3D CAD modeling leads to increased scores on tests of spatial reasoning skills

Interventions do not necessarily need to be computer-based to be effective; technical drawing, 3D modeling with craft materials, and drafting activities have been shown to help develop and improve spatial skills. See, for example, Contero, et al. (2006); Donohue (2010); Martín-Dorta, Saorín, and Contero (2008); and Olkun (2003). These studies serve as a reminder that effective interventions can also be low-cost and accessible, an important point to practitioners operating in resource-challenged environments.

### *Recommendations for Practitioners*

As stated at the beginning of this overview, possession and use of good to excellent levels of spatial skills are essential to success in engineering studies. Skill assessment and remediation should be integral parts in the curriculum. Recent research results provide practitioners with strong arguments to counter arguments of overcrowded curricula and limited resources. Validated assessment instruments are widely available (*cf.* Yue, 2006), remediation can be achieved within weeks, and remediation activities run the gamut from low- (e.g., technical drawing) to high- (e.g., 3D CAD) tech/cost solutions. Summer sessions, summer camps, BRIDGE, January term (intersession/J-term), and other mini-mester (Maymester) provide excellent opportunities for offering remedial courses. Assessment of spatial skills can be another placement test performed during orientation. Basic factors affecting student persistence/retention in undergraduate engineering studies – self confidence (Astin, 1993; Besterfield-Sacre, Atman, & Shuman, 1997; Felder, Felder, & Dietz, 1998) and attitudes towards engineering (Besterfield-Sacre, Atman, & Shuman, 1997; Burtner, 2004) – are likely to be supported by initiatives to strengthen spatial skills.

Spatial skills are also another dimension to consider in recruitment initiatives; research has shown that adding spatial abilities to traditional predictors of student success in undergraduate engineering studies such as high school/first-year core course grades and SAT scores (Besterfield-Sacre, Atman, & Shuman, 1997) help identify students with the potential to study engineering. This finding provides an argument for implementing assessment and remediation activities in the P-12 curriculum.

### **Current and Future Research Areas**

The work done in identifying the role of working memory with performance on tests of spatial skills by Kaufman (2007) is enlarged upon by Gyselinck, et al. (2009) and Meneghetti, et al. (2009). Renewed attention regarding the connection between cognitive styles and spatial abilities is also observed; see, for example, Blazhenkova and Kozhevnikov (2009); Kozhevnikov, Blazhenkova, and Becker (2010); Kyritsis, et al. (2009); Sorby (2009); and Yoon and D'Souza (2009).

Additional research on the factors affecting the development of spatial skills and innovative methods for overcoming obstacles to their development would help us advance our understanding as to the factors which do have a definitive impact on the development and use of spatial skills. We need to move further beyond the surface explanation of gender as the factor making a difference. Advances in neurobiology and neuropsychology, for example, will allow researchers to develop models of development and performance that are as complex as is the concept of spatial skills.

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