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Literature Overview
Spatial Skills: A Focus on Gender and Engineering

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Introduction

Strong spatial-visualization skills, particularly the ability to visualize in three dimensions, are cognitive skills that are linked to success in science, technology, engineering, and mathematics (STEM) fields. Well-developed math and verbal skills are recognized as necessary for success in STEM, and the National Science Board (2010) maintains that spatial skills should be added to this list. Unfortunately, significant gender disparities exist on spatial-skills test performance and are most evident in mental rotation, an important skill in engineering.

Poor performance on spatial-visualization tasks can directly affect perceptions of self-efficacy, especially in women and individuals from lower socioeconomic groups (Hsi, Linn, & Bell, 1997; Rafi & Samsudin, 2007; Sorby, 2009; Towle et al., 2005). Students who have the opportunity to improve their spatial-visualization skills demonstrate greater self-efficacy and are more likely to persist in engineering (Hsi et al., 1997). Research has demonstrated that training is an effective way to improve spatial-visualization skills, and gender differences are eliminated as a result of interventions using both technology and manual strategies (Hand, Uttal, Marulis, & Newcombe, 2008; Hsi et al., 1997; Newcombe, 2006; Onyancha, Derov, & Kinsey, 2009; Sorby, 2009; Sorby & Baartmans 2000; Terlecki, Newcombe, & Little, 2008). Lower levels of ability in this area may be attributed to lack of childhood exposure to three-dimensional (3-D) video games, construction toys, certain sports, shop drafting, and sketching and mechanics classes (Okagaki & Frensch 1994; Sorby, 2009).

This literature overview covers the following topics:

- Definition of spatial skills
- Gender differences
- Spatial-skill ability and success in engineering
- Methods for assessing spatial skills
- Enhancing spatial-skills development: Recommendations for engineering schools
- Enhancing spatial-skills development: Recommendations for practitioners

Definition of Spatial Skills

Sorby (1999) discusses the difference between "spatial abilities" and "spatial skills." Although the terms are often used interchangeably, *abilities* refers to innate characteristics, implying that someone is born with the ability or inability and cannot learn it, while *skills* connotes learned characteristics, implying that the skill can be improved with practice. Since extensive research supports the latter, the term "skills" will be used throughout this document.

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In general, spatial skills refer to a collection of cognitive, perceptual, and visualization skills. The traditional focus of research on spatial skills dealt with understanding and manipulation of 2-D and, to a lesser extent, 3-D space (Olkun, 2003; Sorby, 1999). However, advances in computer architecture, processor speed, and applications during the past several decades made 3-D design software more accessible to students, shifting the research focus to 3-D space. While lists differ, and there is no uniform definition, substantial agreement exists that the core spatial skills are the following (Sutton & Williams, 2008, p. 115):

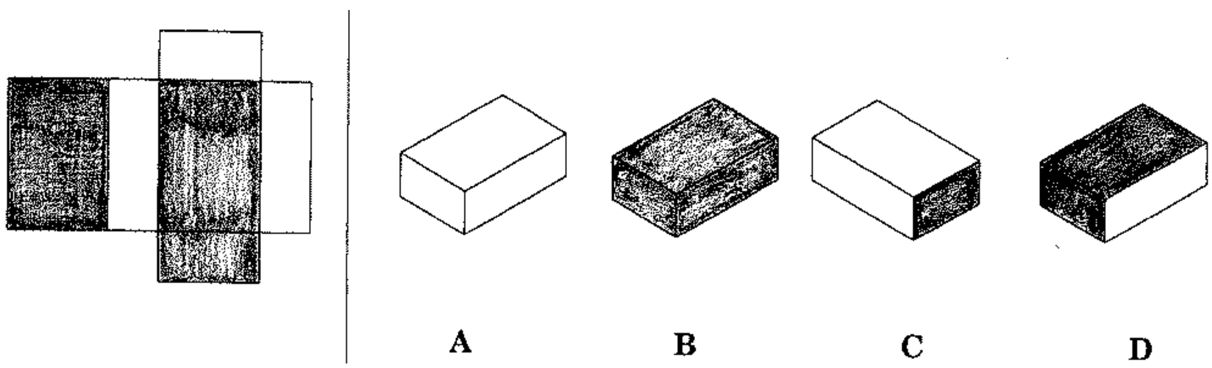
- the ability to visualize mental rotation of objects
- the ability to understand how objects appear in different positions
- the ability to conceptualize how objects relate to each other in space
- the ability to understand objects in 3-D space

To assess and research spatial-skills proficiency a number of researchers have collapsed these four core spatial skills into two classifications: spatial visualization and spatial relations (Burnet & Lane, 1980; Clements & Battista, 1992; McGee, 1979; Olkun, 2003; Pellegrino, Alderton, & Shute, 1984). These classifications are defined and illustrated below.

- **Spatial visualization**

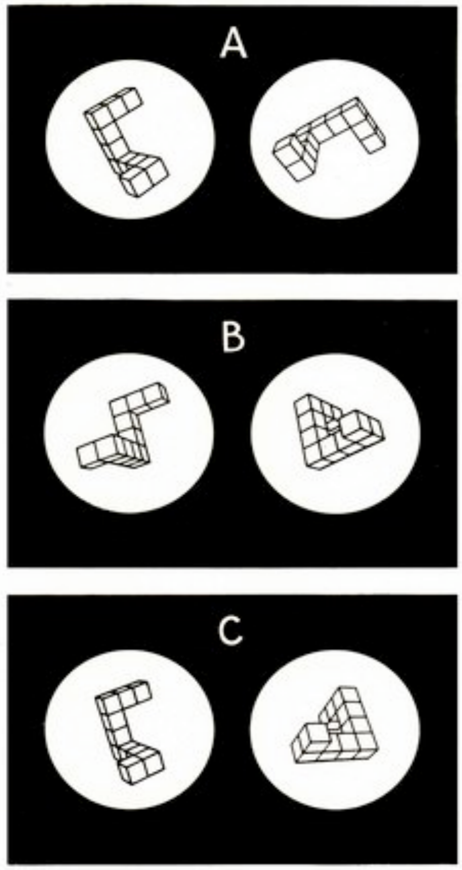
The ability to imagine rotations of objects or their parts in 3-D space by folding and unfolding (Martín-Dorta, Saorín, & Contero, 2008, p. 506; see figure 1).

Figure 1.
Spatial-visualization test example from the DAT-SR (Bennett, Seashore, & Wesman, 1947).



- **Spatial relations:** The ability to imagine rotations of 2-D and 3-D objects as a whole body, which includes mental rotation and spatial perception (Martín-Dorta et al., 2008, p. 506).

Figure 2.
Spatial-relations test example from Generic Mental Rotation Tasks (Shepard & Metzler, 1971, p. 702).



A discussion on test selection is included in the section on Methods for Assessing Spatial Skills below.

Gender Differences

Linn and Petersen's meta-analysis (1986) of studies conducted between 1974 and 1982 determined that men perform better than women on tests of spatial perception and mental rotation, and men and women perform equally well on spatial-visualization tests. Masters and Sanders (1993) confirmed the strong difference by gender on performance of mental rotation. Using meta-analytic techniques, they found that males performed significantly higher than women in all 14 studies that administered the Vandenberg Mental Rotations Test (Vandenberg & Kuse, 1978) to adolescents and young adults between 1975 and 1992. In an analysis of more than 50 years of research, Voyer, Voyer and Bryden (1995) again found sex differences, with males scoring higher than women in tests that assess mental rotation and spatial-perception skills. The ability to mentally rotate 3-D objects is especially important in engineering, and this skill has the greatest gender disparity in spatial-skills performance, favoring males (Sorby, 2009).

Various researchers have suggested that gender differences in spatial skills may be transmitted as a recessive characteristic on the X chromosome, that these differences are related to a male sex hormone, or that they are the result of environmental factors (Bergvall, Sorby, & Worthen, 1994). These findings were not supported in the Linn and Peterson meta-analysis (1986), nor has the present literature review found support for this premise.

Empirical support, however, can be found for environmental influences on spatial-skill ability. Research indicates that manipulation of environmental factors, such as childhood play and educational experience, can increase scores for both genders and reduce the score gap between genders. Vasta, Knott, and Gaze (1996, p. 550) postulate, "If the gender differences on the spatial tasks can be substantially reduced or eliminated through programmed experiences such as training, it becomes theoretically more likely that the performance differences derive primarily from socialization and, even more so, that they do not reflect fundamental differences in competencies between males and females." Baenninger and Newcombe's meta-analysis (1989) found spatial-activity participation to be related to spatial skill for both sexes, supporting Vasta et al. (1996).

Test scores may also be improved, and gender differences reduced, through manipulating the testing environment. Sharps, Welton and Price (1993) and later Sharps, Price, and Williams (1994) identified the importance of instructions for testing outcomes. In their experiments, when subjects were told simply to solve the problems on the test, as opposed to using their various spatial-skills abilities to solve problems that required rotating objects, no sex differences in performing mental image rotation tasks appeared. Hamilton (1995) confirmed these findings, reporting that instructions that included discussions of solving spatial tasks decreased scores for women but not for men. When the spatial characteristics on the tests were minimized in the instructions, no significant differences were found between men and women on spatial memory or mental image rotation. Furthermore, emphasis on the tested abilities as useful for male-stereotyped occupations produced a large gender gap in scores. If the abilities were instead described in relation to female-stereotyped occupations, the gender gap was reduced to a small and insignificant difference.

These studies indicate the presence of stereotype threat. According to stereotype threat theory, a person's performance on a task may be compromised if there is the potential to confirm a negative stereotype about the group with whom she or he identifies (for example, women have low ability in spatial skills; Steele & Aronson, 1995). McGlone and Aronson (2006) found that female undergraduates who received reminders about their identity as a student at a selective private college before taking the Vandenberg MRT did better than females who were reminded about their gender only or a test-irrelevant identity. The results were 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 skill level, but have different reactions to reminders. These results are verified by Moe (2009).

Voyer et al. (1995) found that gender differences in performance start appearing by age 13 and increase with age. This suggests that the longer a person has to internalize stereotypes associated with gender differences in spatial skills, the more impact the stereotypes have on performance. In addition, basic factors affecting student persistence and retention in undergraduate engineering studies such as self-confidence (Astin, 1993; Besterfield-Sacre, Atman, & Shuman, 1997; Felder, Felder, & Dietz, 1998) and attitudes towards engineering (Besterfield-Sacre et al., 1997; Burtner, 2004) are likely to be supported by strengthening students' spatial skills.

Although the performance gap on mental rotation tests, particularly with respect to 3-D objects, persists (Contero, Naya, Company, & Saorín, 2006; Immekus & Maller, 2010; Sutton, Williams, & McBride, 2009), evidence shows that the gender gap in performance on spatial-visualization tests is closing, especially after training. Using longitudinal data from Michigan Tech (1996 to 2009), where all first-year engineering students have taken the Purdue Spatial Visualization Test: Rotations (PSVT:R; Guay, 1977) since 2000, Sorby and Veurink (2010) found that the average test score is increasing for young women and their failure rate is decreasing. While these results are encouraging, there are statistically significant gender differences, favoring males, on the following PSVT:R data: the percentage of students who receive perfect scores, failure rates, and average test scores. Interestingly, results from background questionnaires administered periodically to Michigan Tech students since 1993 related to computer or video game-playing suggest that the significance of these activities in developing 3-D spatial skills is increasing over time. Sorby and Veurink (2010) indicate that this is likely due to changes in the sophistication and quality of 3-D representations in games over the past decade and student access to these games. Furthermore, the researchers suggest that game playing could be especially beneficial for women, compared to men, in developing 3-D spatial skills.

Spatial-Skill Ability and Success in Engineering

Visual-spatial skills are considered necessary and vital for success in engineering and other STEM courses (Hsi et al., 1997; Miller & Bertoline, 1991; Sorby & Baartmans, 2000). Peters, Chisholm, and Laeng (1994) found in one sample that engineering students performed better on the Vandenberg MRT than did students pursuing Bachelor of Arts degrees and that male engineering students also outperformed female engineering students. In this study the difference in scores did not translate into better course grades. Other studies show a connection between grades and visual-spatial scores (Hsi et al., 1997; Sorby & Baartmans, 2000). In their six-year longitudinal study of spatial-visualization education, Sorby and Baartmans (2000) found that the single most significant predictor of success in the first year graphics course at Michigan Technological University was the PSVT:R, a test that consistently produced gender differences in their samples. The two other significant factors they found were the math ACT subtest score and a combination of prior experiences in shop, drafting, and solid geometry (experienced by more males than females). At MTU, 80% of students who did poorly in their first engineering graphics course did not persist in engineering but transferred to another major (Sorby, 2009). In a study by Agogino and Hsi (1995) faculty maintained that engineering graphics should be considered a gateway course because it has such a large impact on student retention.

Studies also indicate that the addition of spatial skills to traditional predictors for success in engineering—most notably, math and verbal skills—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) reported 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) found 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).

Methods for Assessing Spatial Skills

Practitioners need to be able to assess spatial skill levels using appropriate instruments and identify and implement appropriate interventions to effectively encourage the development and enhancement of spatial skills. Voyer et al. (1995) provided a discussion regarding the efficacy of various assessment methods. Eliot and Smith (1983) included an extensive discussion of tests and assessment methods that can be used to guide the selection of appropriate assessments. The tests most mentioned in recent research are the DAT-SR, Mental Cutting Test, Vandenberg MRT, and PVST:R (Contero et al., 2006; Martín-Dorta et al., 2008; Németh, 2007; Sorby, 1999, 2007; Sorby & Baartmans, 2000; Sorby & Veurink, 2010).

From a practical standpoint, Sheryl Sorby (personal communication, June 2011), a noted spatial-skills researcher, uses the PSVT:R since mental rotation ability has been shown to be particularly important for success in engineering and that's where the largest gender differences are found. Richard Onyancha (personal communication, June 2011), a professor from Rose-Hulman who has done significant work in spatial-skills assessment and analysis, suggests that the following questions be considered when evaluating the type of test to use:

- Has the test been validated for a sufficiently long enough time?
- Is the test at the right level for my target audience?
- Is the content general enough for my target audience or too restrictive?
- Can more than one topic or theme be tested?
- Can the data be analyzed easily?
- Is cost and availability reasonable?

Enhancing Spatial-Skills Development: Recommendations for Engineering Schools

Research shows (Contero et al., 2006; Ferguson, Ball, McDaniel, & Anderson, 2008; Hsi et al., 1997; Martín-Dorta et al., 2008; Onyancha, Derov, et al., 2009; Onyancha, Towle, & Kinsey, 2007) that spatial skills can be improved through training, including research in the area of mental rotation (Sorby & Baartmans 2000; Sorby, Drummer, Hungwe, Parolini, & Molzan, 2006), the skill for which the largest gender gap in performance exists. Interventions do not necessarily need to be computer-based to be effective. Technical drawing, 3-D modeling with craft materials, and drafting activities have been shown to help develop and improve spatial skills (Contero et al., 2006; Donohue, 2010; Martín-Dorta et al., 2008; Olkun, 2003; Sorby & Baartmans, 2000). These studies serve as a reminder that effective interventions can also be low-cost and accessible, an important point for educators operating in resource-challenged environments.

Since visual-spatial skills are important for all engineering students but do not account for the large degree of underrepresentation of women in engineering, there are only a limited number of examples to draw upon. Of those for which published material is available, the following two are prominent and have evidence of success. One example of an intervention that benefits male and female students (but in which women find disproportionate benefits, reducing the gender gap in scores) can be found at Michigan Technological University, where Baartmans and Sorby designed a successful course to improve spatial abilities of engineering students (Sorby & Baartmans, 2000; Sorby, 2011). This three-credit course consists of two hours of lecture and two hours of computer lab per week each term. Other course formats have been used effectively as well (see page 8). Details about the class and resources used can be found in the authors' publications about the project and in *Introduction to 3-D Spatial Visualization* (Baartmans & Sorby, 1996).

Another example is found in the three-hour workshop of Hsi et al. (1997). Based on the "scaffolded knowledge integration" framework, their spatial-strategy instruction includes the following: a) teaching a repertoire of spatial strategies to make the process of distinguishing strategies and thinking about spatial problems visible; b) encouraging students to monitor their own progress and recognize their spatial reasoning strengths and weaknesses as independent learners; and c) and taking advantage of social support for learning. Provided during the semester for low-scoring students in their introductory engineering graphics course at the University of California at Berkeley, the workshop effectively eliminated previously established gender differences in spatial-reasoning task scores.

The preponderance of evidence asserting the connection between spatial-skills development and success in engineering provides strong support for engineering schools to assess students' spatial skills and remediate accordingly. Recent research results provide faculty and other practitioners with strong evidence to counter arguments of overcrowded curricula and limited resources. Validated assessment instruments are widely available (Yue, 2006), and engineering schools should consider adding a twenty-minute spatial-skills assessment test to placement testing that typically occurs during orientation. Remediation can be achieved within weeks, and remediation activities run the gamut from low- (technical drawing) to high- (3-D computer-assisted design) tech cost solutions. One-credit courses, summer sessions, summer camps, and BRIDGE programs provide excellent opportunities for offering spatial-skills training courses.

Twenty engineering schools currently participate in ENGAGE, Engaging Students in Engineering, an National Science Foundation-funded project (www.EngageEngineering.org). The overarching goal of ENGAGE is to increase the capacity of engineering schools to retain undergraduate students by facilitating the implementation of three research-based strategies, one of which is to improve students' spatial skills. All schools have committed to developing a program to assess students' spatial skills and subsequently provide training to those students who possess weaker skills. Five ENGAGE schools have documented their experiences, lessons learned, and future plans after implementing a pilot spatial-skills course (Metz et al., 2011). These schools use Baartmans and Sorby (1996) as the basis for a spatial-skills course and the PSVT:R to assess students' skills.

The biggest challenge schools encountered during this pilot phase was a low enrollment in voluntary spatial-skills courses. Schools are working to address this problem through various strategies. In addition to working through channels to make a spatial-skills training course a requirement, one successful strategy used by Virginia Tech in its pilot course involved an "opt-out" approach. Freshmen who had low scores on the PSVT:R were automatically enrolled in the voluntary spatial-skills course. Although they had the option to drop the course, the majority of students, about 67%, elected to stay enrolled.

In a recent ENGAGE webinar, Sorby (2011) provides the following recommendations to engineering school interested in improving the spatial skill level of their students:

- **Assess the spatial skill level of your incoming engineering students**
  - Identify those with weak skills (60 to 70% on the PSVT:R).
  - Target your efforts at students with weak skills. If you provide training to all students, those who don't need it may be bored, and those who do need it may become even more discouraged, resulting in lower self-efficacy.

- **Formats for instruction that will work**
  - Offer a course for credit for spatial-skills training
  - Require supplemental instruction sessions for students with weak skills, similar to requiring tutoring sessions for students with weak math skills
  - Provide spatial-skills training as part of a summer bridge program
  - Integrate spatial-skills training into a required course only if most of your students have weak spatial skills and not if only a small percentage of students require this training
  - Although a voluntary course option is discouraged, if this is the only course of action, results will improve if a grade is given and attendance is mandatory so students take the course seriously. Also consider the opt-out option described above.

Enhancing Spatial-Skills Development: Recommendations for Practitioners

Identifying factors that affect the development and exercise of spatial skills has traditionally focused on gender differences in performance. Recent research efforts, however, indicate that other characteristics, such as working-memory capacity and socioeconomic status may be involved (Levine, Vasilyeva, Lourenco, Newcombe, & Huttenlocher, 2005). Activities that have been found to improve spatial skills include the following:

- Playing video games (Feng, Spence, & Pratt, 2007; Sorby & Veurink, 2010)
- Having musical experiences (Robichaux, 2002)
- Creating artwork (Caldera et al., 1999)
- Playing with certain toys, such as Legos, Lincoln Logs, and Erector Sets (Sorby & Baartmans, 2000)

Precollege participation in activities relying on hand-eye coordination tends to be high among postsecondary students with good to excellent spatial skills. Men are more likely than women to participate in these activities:

- Certain sports, such as basketball (Lord & Garrison, 1998)
- Technical education and industrial arts classes (Sorby, 1999; Sorby, 2007)

Hill, Corbett, and St. Rose (2010) recommend that parents, teachers, and volunteers of professional organizations do the following:

- Explain to all young people that spatial skills are not innate but developed.
- Encourage all children and students to play with construction toys, take things apart and put them back together again, play games that involve fitting objects into different places, draw, and work with their hands.
- Use handheld models when possible (rather than computer models) to help students visualize what they see on paper in front of them.

Evidence for improving spatial skills comes from research on practice, training, and education (Baenninger & Newcombe, 1989; Bergvall et al., 1994; Sorby, 1999). In their results from a six-year longitudinal assessment of a course to help engineering students overcome deficiencies in 3-D spatial visualization, Sorby and Baartmans (2000) show that participating students scored better on several tests of spatial skill. Retention rates were improved for both male and female students, but more so for women. Factors that make educational efforts effective include administering at least three or four sessions referring directly to a single spatial measure (Baenninger & Newcombe, 1989), allowing for practice and providing feedback (Law, Pellegrino & Hunt, 1993), or simply allowing a student time and guidance to discover the solution (Vasta et al., 1996). The underlying reason for success with these educational approaches may be that they increase the number of strategies from which students may both choose and implement efficient, effective problem-solving processes. This increase may be especially beneficial to women whose life experiences have not provided them with as many strategies for solving the test questions as their male counterparts' experiences have (Linn & Peterson, 1985).

Research results on spatially related activities are not entirely consistent. For example, Deno (1995) created the Spatial Experience Inventory (SEI) to collect information for 480 spatial activities in three categories (formal academic subjects, nonacademic activities, and sports) spanning elementary through postsecondary education. When the sum of all 480 activities was taken into account without considering gender, the relationship between mental rotations scores and visual spatial activities was significant. When the 480 activities were broken down, the only activities that were found to be significantly related to mental rotations skills for women were watching *Sesame Street* and other educational TV shows, manufacturing coursework, building train sets, navigating a car, and playing video games.

Operating under the premise that spatial skills are malleable and, therefore, affected by education or life experience, Hand et al. (2008) conducted a systematic meta-analysis. They included 200 studies, 50 of which were unpublished to avoid biased conclusions, and found that spatial skills respond very well to training and endure over time in both children and adults, although starting before age 13 has an even greater impact.

Conclusion

There are individuals who have strong innate spatial visualization skills, and others who have access to experiences that foster their ability to visualize spatially at a very competent level. However, when students who are otherwise successful academically, struggle with spatial skills in STEM courses that their peers find relatively effortless, they are often discouraged from pursuing study in STEM fields. This circumstance most often occurs with women and individuals from lower socio-economic groups. The key issue is that spatial visualization skills, like other cognitive skills can be learned.

All elementary and secondary school students, especially female students and individuals from low socioeconomic groups, should have access to and be encouraged to participate in activities that develop spatial skills to increase their comfort level, confidence, and self-efficacy to pursue study in STEM disciplines. At the college level, students should be required to take a spatial-skills assessment test and subsequently offered the option to enroll in a course to strengthen their skills to improve persistence and retention. Furthermore, research supports the possibility that if the spatial skills of students with many diverse interests were strengthened, more students might opt to major in STEM fields.

References

Agogino, A. M., & Hsi, S. (1995). *Learning style based innovations to improve retention of female engineering students in the synthesis coalition*. Retrieved from http://www.iwitts.org/component/zoo/item/learning-style-based-innovations-to-improve-retention-of-female-engineering-students

Astin, A. W. (1993, September). Engineering outcomes. *ASEE Prism*, 27–30.

Baartmans, B. J., & Sorby, S. A. (1996). *Introduction to 3D spatial visualization*. Englewood Cliffs, NJ: Prentice Hall.

Baenninger, M., & Newcombe, N. (1989). The role of experience in spatial test performance: A meta-analysis. *Sex Roles, 20*(5/6), 327–44.

Bennett, G. K., Seashore, H. G., & Wesman, A. G. (1947). *Differential aptitude tests*, Forms S and T. New York, NY: The Psychological Corporation.

Bergvall, V. L., Sorby, S. A., & Worthen, J. B. (1994). Thawing the freezing climate for women in engineering education: Views from both sides of the desk. *Journal of Women and Minorities in Science and Engineering, 1*, 323–46.

Besterfield-Sacre, M., Atman, C. J., & Shuman, L. J. (1997). Characteristics of freshman engineering students: Models for determining student attrition in engineering. *Journal of Engineering Education, 86*(2), 139–49.

Burnet, S. A., & Lane, D. M. (1980). Effects of academic instruction on spatial visualization. *Intelligence, 4*, 233–42.

Burtner, J. (2004). Critical-To-Quality Factors Associated With Engineering Student Persistence: The Influence of Freshman Attitudes. *Proceedings of the 34th Annual Frontiers in Education Conference*, *2*, F2E1-F2E5.

Caldera, Y. M., Culp, A. M., O'Brian, M., Truglio, R. T., Alvarez, M., & Huston, A. C. (1999). Children's play preferences, construction play with blocks, and visual-spatial skills: Are they related? *International Journal of Behavioral Development, 23*(4), 855–72.

Clements, D. H., & Battista, M. T. (1992). Geometry and spatial reasoning. In D. Grouws (Ed.), *Handbook of research on mathematics teaching and learning*, pp. 420–64. New York, NY: Macmillan Publishing Company.

Contero, M., Naya, F., Company, P., & Saorín, J. L. (2006). Learning support tools for developing spatial abilities in engineering design. *International Journal of Engineering Education, 22*(3), 470–77.

Deno, J. A. (1995). The relationship of previous experiences to spatial visualization ability. *Engineering Design Graphics Journal, 59*(3), 5–17.

Donohue,S.K. (2010). Work in progress: Identifying undergraduate courses which develop and enhance spatial abilities. *Proceedings of the 40th Annual Frontiers in Education,* F4E1 – F4E2.

Eliot, J., & Smith, I. M. (1983). *An international directory of spatial tests*. Windsor, Berkshire, UK: NFER-NELSON Publishing Company. (Out of print; available at http://drc.ohiolink.edu/handle/2374.OX/30660)

Felder, R. M., Felder, G. M., & Dietz, E. J. (1998, October). A longitudinal study of engineering student performance and retention. V. Comparisons with traditionally-taught students. *Journal of Engineering Education, 87*(4), 469–80.

Feng, J., Spence, I., & Pratt, J. (2007). Playing an action video game reduces gender differences in spatial cognition. *Psychological Science, 18*(10), 850–55.

Ferguson,C., Ball,A., McDaniel,W., & Anderson, R. (2008). A comparison of instructional methods for improving the spatial-visualization ability of freshman technology seminar students." *Proceedings of the IAJC-IJME International Conference.*

Field, B.W. (2007). Visualization, intuition, and mathematics metrics as predictors of undergraduate engineering design performance. *Journal of Mechanical Design 129*(7), 735– 743.

Guay, R. B. (1977). *Purdue Spatial Visualization Test: Rotations*. West Lafayette, IN: Purdue Research Foundation.

Hamilton, C.J. (1995). Beyond sex differences in visuo-spatial processing: The impact of gender trait possession. *British Journal of Psychology*, *86*(1), 1-20.

Hand, L. L, Uttal, D. H., Marulis, L., & Newcombe, N. S. (2008). *A meta-analysis of training effects on spatial skills.* Presented at the annual meetings of the Association for Psychological Science, Chicago.

Hill, C., Corbett, C., & St. Rose, A., (2010). *Why so few? Women in science, engineering technology and mathematics.* Washington, DC: AAUW.

Hsi, S., Linn, M. C., & Bell, J. E. (1997). The role of spatial reasoning in engineering and the design of spatial instruction. *Journal of Engineering Education, 86*(2), 151–58.

Humphreys, L. G., Lubinski, D., & Yao, G. (1993). Utility of predicting group membership and the role of spatial visualization in becoming an engineer, physical scientist, or artist. *Journal of Applied Psychology, 78*(2), 250–61.

Immekus, J. C., & Maller, S. J. (2010). Factor structure invariance of the Kaufman Adolescent and Adult Intelligence Test across male and female samples. *Educational and Psychological Measurement, 70,* 91–104.

Law, D. J., Pellegrino, J. W., & Hunt, E. B. (1993). Comparing the tortoise and the hare: Gender differences and experience in dynamic spatial reasoning tasks. *Psychological Science, 4*(1), 35-40.

Levine, S. C., Vasilyeva, M., Lourenco, S. F., Newcombe, N. S., & Huttenlocher, J. (2005). Socioeconomic status modifies the sex difference in spatial skill. *Psychological Science, 16*(11), 841–45.

Linn, M. C., & Petersen, A.C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development, 56*(6)*,* 1479–98.

Linn, M. C., & Petersen, A. C. (1986). A meta-analysis of gender differences in spatial ability: Implications for mathematics and science achievement. In J. S. Hyde & M. C. Linn (Eds.), *The psychology of gender: Advances through meta-analysis* (pp. 67–101). Baltimore, MD: Johns Hopkins University Press.

Lord, T. R., & Garrison, J. (1998, June). Comparing spatial abilities of collegiate athletes in different sports. *Perceptual Motor Skills Journal, 86*(3, Pt. 1), 1016–8.

Martín-Dorta, N., Saorín, S. J., & Contero, M. (2008). Development of a fast remedial course to improve the spatial abilities of engineering students. *Journal of Engineering Education, 97*(4), 505–13.

Masters, M. S., & Sanders, B. (1993). Is the gender difference in mental rotation disappearing? *Behavior Genetics*, *23*(4), 337–41.

McGee, M. G. (1979). Human spatial abilities: Psychometric studies and environmental, genetic, hormonal, and neurological influences. *Psychological Bulletin, 86,* 889–918.

McGlone, M. S., & Aronson, J. (2006). Stereotype threat, identity salience, and spatial reasoning. *Journal of Applied Developmental Psychology, 27*(5), 486–93.

Metz, S.S., Sorby, S.A., Berry,T., Seepersad, C., Dison, A.M., Allam, Y., Merrill, J., Peters,W., Pfister-Altschul, E., Baxter, S., Zhang, G., and Leach, J. (2011). Implementing Strategies to Improve Retention: Focus on Spatial Skills-Engineering Schools Discuss Successes and Challenges. *Proceedings of the 118th ASEE Conference and Exposition.*

Miller, C. L., & Bertoline, G. R. (1991). Spatial visualization research and theories: Their importance in the development of an engineering and technical design graphics curriculum model. *Engineering Design Graphics Journal, 55*(3), 5–14.

Moe, A. (2009). Are males always better than females in mental rotation? Exploring a gender belief explanation. *Learning and Individual Differences, 19*(1), 21–7.

National Science Board (2010). *Preparing the next generation of STEM innovators: Identifying and developing our nation's human capital.* Retrieved from http://www.nsf.gov/nsb/publications/2010/nsb1033.pdf

Németh, B. (2007). Measurement of the development of spatial ability by mental cutting test. *Annales Mathematicae et Informaticae, 34*, 123–8.

Newcombe, N. (2006). A plea for spatial literacy. *The Chronicle of Higher Education*. Retrieved from http://www.itwitts.com/html/079newcomb.pdf

Okagaki, L., & Frensch, P. (1994). Effects of video game playing in measures of spatial performance: Gender effects in late adolescence**.** *Journal of Applied Developmental Psychology, 15*, 33–58.

Olkun, S. (2003, April). Making connections: Improving spatial abilities with engineering drawing activities. *International Journal of Mathematics Teaching and Learning*, 1–10.

Onyancha, R., Towle, E., & Kinsey, B. (2007). Improvement of spatial ability using innovative tools: Alternative view screen and physical model rotator. *Proceedings of the 114th ASEE Conference and Exposition.*

Onyancha, R. M., Derov, M., & Kinsey, B. L. (2009). Improvements in spatial ability as a result of targeted training and computer-aided design software use: Analyses of object geometries and rotation types. *Journal of Engineering Education, 98*(2), 157–67.

Pellegrino, J., Alderton, D., & Shute,V. (1984). Understanding spatial ability. *Educational Psychologist, 19*(3), 239–53.

Peters, M., Chisholm, P., & Laeng, B. (1994). Spatial ability, student gender, and academic performance. *Journal of Engineering Education, 83*(1), 1–5.

Rafi,A., & Samsudin, K.A. (2007). The relationships of spatial experience, previous

mathematics achievement, and gender with perceived ability in learning engineering drawing. *Journal of Technology Education*, *18*(2), 53-67.

Robichaux, R. (2002). Predictors of spatial visualization: Structural equations modeling test of background variables. *Journal of Integrative Psychology, 2*(2).

Sharps, M. J., Price, J. L., & Williams, J. K. (1994). Spatial cognition and gender: Instructional and stimulus influences on mental image rotation performance. *Psychology of Women Quarterly, 18*, 413–25.

Sharps, M. J., Welton, A. L., & Price, J. L (1993). Gender and task in the determination of spatial cognitive performance. *Psychology of Women Quarterly, 17*, 71–83.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three dimensional objects. *Science, 171*(972), 701–03.

Sorby, S. A. (1999). Developing 3D spatial visualization skills. *Engineering Design Graphics Journal, 63*(2), 21–32.

Sorby, S. A. (2007). Developing 3D spatial skills for engineering students. *Australasian Journal of Engineering Education, 13*(1), 1–11.

Sorby, S. A. (2009). Educational research in developing 3-D spatial skills for engineering students. *International Journal of Science Education, 31*(3).

Sorby, S. A., (2011, January 27). *ENGAGE webinar: Improving spatial visualization skills*. Retrieved from http://www.engageengineering.org/?page=26

Sorby, S. A., & Baartmans, B. J. (2000). The development and assessment of a course for enhancing the 3-D spatial visualization skills of first year engineering students. *Journal of Engineering Education, (89)*3, 301–7.

Sorby, S. A., Drummer, T., Hungwe, K., Parolini, L., & Molzan, R. (2006). Preparing for engineering studies: Improving the 3D spatial skills of K–12 students. *Proceedings of the 9th International Conference on Engineering Education, T3E-6–T3E-10.*

Sorby, S. A., & Veurink, N. (2010). Are the visualization skills of first-year engineering students changing? *Proceedings of the 117th ASEE Conference and Exposition*.

Steele, C. M., & Aronson, J. (1995). Stereotype threat and the intellectual test performance of African-Americans. *Journal of Personality and Social Psychology, 69,* 797–811.

Sutton, K., & Williams, A. (2008). Developing a discipline-based measure of visualization. *UniServe Science Proceedings*, 115–20.

Sutton, K. J., Williams, A., & McBride, W. (2009). Spatial ability performance of female engineering students. *Proceedings of the 20th Australasian Association for Engineering Education Conference*.

Terlecki, M., Newcombe, N., & Little, M. (2008). Durable and generalized effects of spatial experience on mental rotation: Gender differences in growth patterns. *Applied Cognitive Psychology, 22*(7), 996–1013.

Towle, E., Mann, J., Kinsey, B., O'Brien, E., Bauer, C., & Champoux, R. (2005). Assessing the self-efficacy and spatial ability of engineering students from multiple disciplines. *ASEE/IEEE Frontiers in Education Conference, 31*(3), 459-80.

Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills, 47*, 599–604.

Vasta, R., Knott, J. A., & Gaze, C. E. (1996). Can spatial training erase the gender differences on the water-level task? *Psychology of Women Quarterly, 20*, 549–67.

Voyer, D., Voyer, S., & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin, 117*(2), 250–70.

Webb, R. M., Lubinski, D., & Benbow, C. P. (2007). Spatial ability: A neglected dimension in talent searches for intellectually precocious youth. *Journal of Educational Psychology, 99*(2), 397–420.

Yue, J. (2006). Spatial visualization by isometric drawing. *Proceedings of the 2006 IJME-INTERTECH Conference*.