Developing 3-D Spatial Visualization Skills for Non-Engineering Students

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Abstract
The ability to visualize objects and situations in one's mind and to manipulate those images is a cognitive skill vital to many career fields, especially those requiring work with graphical images. Unfortunately, of all cognitive processes that have been investigated, spatial cognition shows some of the most robust gender differences favoring males, especially in the ability to mentally rotate 3-dimensional objects. This has obvious implications for our attempts to encourage gender equity in technical and scientific fields. At Michigan Tech we have been offering a course aimed at improving the 3-D spatial skills of engineering students since 1993. Through a subsequent grant, we developed nine multimedia software and workbook modules for developing 3-D spatial skills. In the Fall of 2004, we were awarded a grant from the National Science Foundation to extend our training materials and activities to students in majors other than engineering and to investigate gender differences in preferred learning/training styles. This paper summarizes the results from our research to date with non-engineering majors and discusses implications for the future.

Background
The ability to visualize objects and situations in one's mind and to manipulate those images is a cognitive skill vital to many career fields, especially those requiring work with graphical images. Evidence suggests that well-developed spatial skills are critical to success in Engineering, Chemistry, Computer Science, Mathematics, Physics, Medicine, Dentistry, and many other fields. Spatial abilities have been widely studied and are known to be fundamental to higher-level thinking, reasoning, and creative processes. Unfortunately, of all cognitive processes that have been investigated, spatial cognition shows some of the most robust gender differences favoring males, especially in the ability to mentally rotate 3-dimensional objects. This has obvious implications for our attempts to encourage gender equity in technical and scientific fields. Recognizing the importance of well-developed spatial skills for technological careers, the National Council of Teachers of Mathematics (NCTM) has included benchmarks regarding the development of spatial abilities within the Pre-college Mathematics Educational Standards (NCTM, 2000) and middle school mathematics education has been a focus of national interest due mainly to the results of the Third International Mathematics and Science Study, and state, national and local standards (Ai, 2002).

Fortunately, although individuals vary in spatial performance, research has shown that most, if not all, of the component skills can be improved through training and practice.

For the project described in this paper, we began research studies to investigate whether materials developed for improving spatial skills for one audience will work with other audiences. The materials that we used in our research studies consist of an established workbook and multimedia software package developed through an NSF grant for use in a first-year engineering course for undergraduate students.

Prior Research in Spatial Cognition.
According to Piagetian theory (Bishop, 1978), spatial skills are developed in three stages. In the first stage, topological skills are acquired. Topological skills are primarily two-dimensional and are acquired by most children by the age of 3-5. With these skills, children are able to recognize an object's closeness to others, its order in a group, and its isolation or enclosure by a larger environment. The second stage involves visualizing three-dimensional objects and perceiving what they will look like from different viewpoints or what they would look like if they were rotated or transformed in space. Most children have typically acquired this skill by adolescence, however, if the object is unfamiliar, many students in high school or even college have difficulty visualizing at this stage of development. In the third stage, people are able to visualize the concepts of area, volume, and distance in combination with those of translation, rotation, and reflection. At this stage, therefore, a person is able to combine measurement concepts with their previously acquired projective skills.

The relationship between spatial ability and success in science and mathematics has been reported in several publications over the past 20 years. A significant body of work in the chemical sciences was undertaken by Bodner and his co-workers in the late 1980s. (Pribyl & Bodner, 1987; Carter, et al, 1987; Bodner & McMillan, 1986). In those studies, it was noted that both spatial ability and gender can play a significant role in the success of students, particularly in entry-level classes such as general chemistry. However, with the exception of a few very recent studies (Yang, Andre, & Greenbowe 2003; Barke & Engida, 2001; Coleman & Gotch, 1998), subsequent work in the chemical sciences has been sparse and only Yang, Andre, & Greenbowe (2003) have really considered the impact of spatial training on the ability of students and their performance in the chemical sciences. Their study considered the impact of computer animations on college students' understanding of electrochemical cells and found that they enhanced understanding.

Studies have shown quite clearly that students with high spatial ability scores performed better on organic chemistry questions requiring problem-solving skills (Small & Morton, 1983; Pribyl & Bodner, 1987). This was particularly true for questions involving the drawing or manipulation of molecular representations, and it was observed that students with higher spatial skills were more likely to draw correct structures and diagrams than those with lower spatial skills. These studies also noted that, as expected, spatial ability had little impact on those questions requiring memorization or simple numerical procedures. It is interesting to note that although a positive relation was observed between spatial ability and achievement, gender was only a significant factor in four out of 60 cases. One might explain this lack of significance by considering the type of student taking organic chemistry, who tend to be a science or engineering major with several years experience and a predisposition toward the sciences. Students with weak spatial skills would likely have been filtered out of the system before taking organic chemistry. Furthermore, since spatial ability can be taught, it is reasonable to assume that organic chemistry students, who have had continued exposure to three-dimensional representations and chemical structures over several years, would have likely developed their spatial skills, regardless of gender.

By one estimate there are at least 84 different careers for which spatial skills play an important role (Smith, 1964). For technical professions, such as engineering, spatial visualization skills and mental rotation abilities are especially important (Maier, 1994). Norman (1994), found that a person's spatial skill level was the most significant predictor of success in his/her ability to interact with and take advantage of the computer interface in performing database manipulations, and Sorby (2000) found that a person's spatial skills are related to his/her ability to effectively learn to use computer aided design software. Eyal and Tendick (2001) found that a person's spatial ability is related to his/her ability to effectively learn how to learn to use the modern-day laparoscopic equipment utilized throughout the medical profession. Tartre (1990) has suggested gender differences in spatial skills may be linked to math performance and indeed, when mental rotation ability was held constant in one study, gender differences in mathematical problem solving disappeared (Casey, Pezaris, & Nuttall, 1992).

Gender Differences in Spatial Skills.

There is a great deal of evidence to suggest that the spatial skills of women lag significantly behind those of their male counterparts. Theories for the cause of these differences include the assertion that spatial ability is transmitted as a recessive characteristic on the X-chromosome (Stafford, 1972), that spatial ability is related to a male sex hormone (Hier & Crowley, 1982), or that environmental factors are the primary reasons for male-female differences in spatial skill levels (Fennema & Sherman, 1977). The truth most likely falls in the interaction of many factors. Because of media reports of research findings, as well as traditional stereotypes, both women and men in Western societies are usually convinced that women are naturally inferior in both mathematical and spatial performance (Jones et al., 1984). Stereotype threat theory (Spencer, Steele, & Quinn, 1999) suggests that performance may suffer if one is in a situation where the requirements of a task go against one's stereotypical role. Women in male-dominated professions do report feeling more threatened by negative stereotypes and also report thinking about changing their major more than males (Steele, James, & Barnett, 2002). This research suggests that female role models and mentors will be important to increasing gender diversity in STEM disciplines. Therefore it is critically important to increase the number of women entering and completing degrees in STEM fields.

Studies by Bodner and McMillen (1986) and by Carter *et al* (1987) support the idea that spatial ability in upper level classes, such as organic chemistry, is less gender dependent than lower level classes, such as general chemistry. Bodner and McMillen found that there were statistically significant correlations between spatial ability and achievement, not only on spatial concepts such as the manipulation of solids, but also on multiple-choice stoichiometry problems. This suggests, therefore, that the spatial ability of students can improve with exposure to spatial concepts and that this can lead to improvements in a student's ability to solve a wide range of scientific problems by improving their ability to identify and restructure relevant information. In the studies by Carter *et al* it was found that gender was often a significant factor in both exams and classroom activities in general chemistry.

In a meta-analysis of spatial studies, Linn and Petersen (1985) found that males outperform females on mental rotation tasks where speed of performance is a factor. Males were more likely to use a "holistic strategy" and females were more likely to use an "analytic strategy." The holistic strategy relies on visualizing the whole object, and the analytic strategy uses a systematic, stepwise approach. The holistic strategy has been found to be more efficient (i.e., less time consuming) in timed tests. Linn and Peterson have therefore concluded that "spatial strategy selection" is a factor in gender differences in mental rotation tasks. Hsi, Linn, and Bell (1997) determined, however, that spatial strategies can be acquired through instruction.

There appears to be a generic shift from 'analytic' to 'holistic' skill that is tied to the development of spatial expertise. Dreyfus & Dreyfus (1986) describe this in terms of a hierarchical skill development model. Hungwe (1999) describes transformations of knowledge and skill over time in machining work that are consistent with the Dreyfus & Dreyfus model. More research is needed to better understand the development of spatial visualization skills and strategy over time. In particular there is a need to understand the role of strategy in skill development and the best ways of teaching strategy to novice learners so that they can perform optimally in school-type assessments. Specific instruction on strategy coupled with practice should help learners to reflect on their learning and become more metacognitively aware of their learning process. These skills are important in the overall development of learners.

There have been several studies examining what type of pre-college activities tend to be present in students who have well developed spatial skills (Deno, 1995, Leopold, Sorby, & Gorska 1996, and Medina, Gerson, & Sorby, 1998). Activities that require eye-to-hand coordination are particularly useful in developing these skills such as: 1) playing with construction toys (e.g., Legos) as a young child, 2) participating in classes such as shop, drafting, or mechanics as a middle school or secondary student, 3) playing 3-dimensional computer games, 4) participating in certain types of sports (e.g., basketball), and 5) having well-developed mathematical skills. Since most of these factors typically have a fairly high degree of gender bias favoring men, it is no wonder that the spatial skills of women often fall behind those of their male peers.

In the Fall of 2004, the authors received a grant from the National Science Foundation to test the methods and materials developed for engineering students with a non-engineering audience. Results from the research conducted to date are presented in the following sections.

Pre-and post-testing
As a technological university, Michigan Tech enrolls approximately 95 percent of its nearly 6000 undergraduate students in engineering, science, or technology with about two-thirds in engineering alone. For this study, first- and second-year students in majors outside of engineering were contacted for participation. The two largest programs outside of engineering are computer science (~325 undergraduates) and biology (~250 undergraduates). In-class presentations were made and mass emails were sent to targeted students who were invited to earn a $15 gift certificate to the Michigan Tech bookstore in exchange for taking a 20-minute spatial skills test. The Purdue Spatial Visualization Test: Rotations (PSVT:R) (Guay, 1977) was used for the pre-testing.

In all 170 students in majors outside of engineering opted to take the pre-test. The students were subsequently divided into three experimental groups and one comparison group. The pre-test scores were balanced across the experimental groups to avoid possible regression to the mean effects in the analysis. The three experimental groups participated in weekly training sessions over a ten-week period using materials originally designed for use in the engineering course. One of the groups used just the workbook, the second group used just the software, and the third group used both the software and the workbook. Students in the experimental groups were also pre-tested with the Mental Cutting Test (MCT) (CEEB, 1939).

At the end of the ten-week training session students were post-tested with both the PSVT:R and the MCT and were administered an attitudinal survey as well. Students in the comparison group were also invited back to take the PSVT:R as a post-test and received an additional $30 gift certificate to the MTU bookstore for their participation.

Results from Pre-/Post-testing
Table 1 indicates data obtained from the pre- and post-testing with the PSVT:R and the MCT for the experimental and comparison groups. It also presents data (GN131 and ME104) obtained from pre- and post-testing conducted associated with two different engineering graphics courses at Michigan Tech (Sorby & Gorska, 1998).

Table 1. Pre-/Post-Test Results

	PSVT:R			MCT		
	Pre-Test	Post-Test	Gain	Pre-Test	Post-Test	Gain
GN131-Graphics Course	77.2	84.7	7.5 ($p<0.005$)	51.4	60.0	8.6 ($p<0.005$)
ME104-Graphics Course	NA	NA	NA	69.8	76.0	6.2 ($p<0.005$)
EG-Software Only	69.5	79.4	8.4 ($p<0.005$)	44.5	59.9	6.5 ($p<0.01$)
EG-Workbook Only	75.9	86.6	11.6 ($p<0.0005$)	53.9	62.3	8.4 ($p<0.001$)
EG-Software & Workbook	74.3	85.6	11.2 ($p<0.0005$)	46.4	60.2	13.8 ($p<0.0005$)
Comparison Group	72.6	77.9	5.3 ($p<0.025$)	NA	NA	NA

As illustrated by the data in Table 1, students in each of the experimental groups made significant gains in their spatial skills as measured by both the MCT and the PSVT:R. Gains were comparable to those achieved by students in traditional engineering graphics courses, and in some cases, better. Students in the Comparison Group made marginally significant gains on the PSVT:R over roughly the same time period.

Our intention was to compare gains across treatment groups and gender using a standard two-way ANOVA. But there were several large gains/losses (up to 13 points) that could be classified as outliers in the data, which inflated the variance and decreased the power of the traditional ANOVA. Also, students with high pretest scores are more likely to decline due to chance than students with low pretest scores, although this effect is probably balanced across the groups.

For these reasons we took another approach to the analysis. We created a binary variable that equaled 1 if the student gained in score, and equaled 0 if they had a negative or zero gain. We then fit a nonparametric logistic regression model, called a generalized additive model (Hastie and Tibshirani, 1990) using this binary variable as the dependent variable with independent variables being group and pretest score. This logistic regression model essentially models the probability of improvement rather than the actual gain. The major advantage of the generalized additive model is that it can capture curvature in the response. Gender was also considered in this analysis; however, gender had no effect on the probability of improvement for either the PSVT:R or MCT gains. Figure 1 illustrates the results from this analysis.

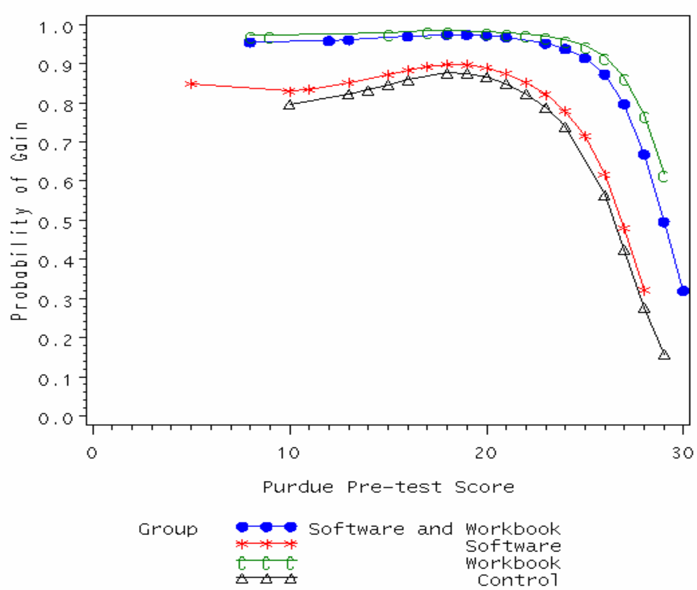

Figure 1. Fitted Logistic Regression Models for the Four Groups

For the PSVT:R gains, both groups that used the workbook were significantly better than the control group (p = 0.04 and p = 0.02), whereas the group using only software was not better than the control group ($p = 0.75$). The workbook only group and workbook and software group were not significantly different, and the control group and software alone group were not significantly different. Note that the curves for the Control Group and the Software Only Group start around 80% and are relatively flat for the students with "low" pre-test scores and that all curves decrease with high pre-test scores, as expected. By this model, if the training has no effect, then we would expect, by chance, about 50% of the students to exhibit gains. One theory is that some learning takes place just by taking the exam, so even the control group can be expected to gain, thus the 80% improvement rate for the control group. Another theory is that all groups should be expected to exhibit gains on the PSVT:R over the course of a semester due to the highly technical and mathematical training each is receiving over a semester through their studies at Michigan Tech. Further research with students in non-technical majors, who are not enrolled in rigorous math and science courses over a semester, could determine the significance of the practice effect in taking the PSVT:R as both a pre- and post-test under these conditions. For the MCT, there were no significant differences between groups or gender ($p > 0.05$), although the response curves exhibited a similar shape to those in Figure 1.

Results of Attitudinal Survey
Upon completion of the lessons and post-test, students completed an eleven question attitudinal survey regarding their experiences. We cross-tabulated responses by gender and treatment type, and for each question compared male and female responses and treatment group responses using a Chi-squared contingency table analysis. We obtained completed questionnaires from 29 females and 66 males.

There was no difference ($p = 0.37$) between males and females regarding which treatment they would have chosen, with 62% of all students expressing preference for the software only group. Students in the software only group expressed significantly higher preference for the software only treatment, 87%, compared to 51% for students in the software and workbook group and 47% in the workbook only group, although "Software Only" was the most frequently selected category for students in all 3 groups. It is interesting to note that the preferred learning mode was in reality the least effective. The reason for this stated preference could be that the time involved in completing the software modules was significantly lower when compared to completion of workbook pages (see following paragraph).

Female students spent significantly more time on the activity than males ($p = 0.01$); 40% of males spent less than one half hour per week compared to 21% of females. Thirty-five percent of females spent one to one and a half hours per week compared to 9% of males. Students in the software only group spent significantly less time per week ($p = 0.01$) than students in the other groups. Seventy-two percent of students in the software only group spent less than one half hour per week compared to 13% in the software and workbook group and 16% of students in the workbook only group.

Male students expressed higher levels of confidence in their visualization abilities (Table 2) at the onset of the study than did females ($p = 0.01$). There was no difference in this response between treatment groups ($p = 0.21$).

Table 2. Level of confidence in ability to do tasks at beginning of study. (Question was asked retrospectively at end of study.)

Level of Confidence	Males (n = 66)	Females (n = 29)
Not Confident	1.5%	27.6%
Somewhat Confident	28.8%	51.7%
Confident	37.9%	20.7%
Most Confident	31.8%	0%

When asked about their level of confidence at the end of the study, male students still expressed a significantly higher level of confidence than female students (p = 0.01), with 53% of male students indicating the highest level of confidence compared to 21% of female students. For female students, 27.6% possessed the lowest level of confidence at study end compared to only 3% of male students. Yet significantly (p = 0.01) more female students, 82.7%, compared to 50% of males, indicated an increase in confidence. This could be due to the high level of confidence expressed by males at the study onset.

Overall only 3% of students indicated that their training was not adequate; 8% of indicated that their training was more than adequate, 59% indicated it was adequate, and 30% indicated the training was somewhat adequate. Low frequency counts in the "not adequate" category invalidated the use of the Chi-square test comparing genders and treatments.

There was no difference between treatment groups regarding their attitude about working alone on the tasks (p = 0.95), but there were significant differences (p = 0.01) between males and females, with more males (73%) preferring to work alone on the activities compared to 38% of females.

There was no difference (p = 0.69) between treatment groups regarding their perceived learning. Overall, 5% of students indicated that they did not learn anything new; 38% indicated that they learned a few aspects, 32% stated that they learned something on most days, and 25% indicated that they learned something every session. Female students were more positive than their male counterparts (p = 0.03), with female students generally expressing higher levels of learning than male students (Table 3).

Table 3. Perceived learning by male and female students.

Level of Learning	Males (n = 66)	Females (n = 29)
Did not learn anything new	6%	3%
Learning limited to a few aspects	47%	17%
Learned something on most days	26%	45%
Learned something every session	21%	35%

Male and female students indicated similar attitudes regarding the relevance of the activity to their field (p = 0.91). Overall 21% indicated that they saw absolutely no relevance, 57% saw some relevance, 18% said the activities were relevant to their field, and 4% thought the activities were most relevant. There were no significant differences between treatment groups (p = 0.31).

Regarding the use of manipulatives (snap cubes), there was no difference between treatment groups (p = 0.80), with 41% of participants stating they did not use manipulatives at all, 37% used the manipulatives only occasionally, 14% use the manipulatives most of the time, and 8% used the manipulatives whenever they were available. Male and female students differed significantly (p = 0.01) in their use of manipulatives, with female students tending to use the manipulatives more than males. Fifty one percent of males never used the manipulatives compared to 17% of females, and 14% of females used manipulatives whenever available compared to 6% of males.

In rating their overall experience, there were no differences between males and females (p = 0.75) nor treatment groups (p = 0.92). Three percent of students rated their overall experience as not useful, 37% as somewhat useful, 47% as useful, and 13% as most useful.

Conclusions

It appears that the software and workbook developed for use in improving the spatial skills for engineering students are also suitable for use with non-engineering students. The students made statistically significant gains on two standardized tests designed to measure spatial skills and self-reported learning from their experiences with the materials. It appears that the gains in spatial skills were not equivalent for each group. Those groups that used the workbook achieved significantly higher gains in test scores compared to the students who used the software only. Gains for the software only group were comparable to those achieved by the control group. Gender differences in gains were not observed, probably due to low sample sizes.

Several gender differences were noted based on results from the attitudinal survey completed by students at the end of the training sessions. In particular, women exhibited significantly higher gains in confidence level when compared to their male counterparts. In addition, women perceived that they learned more and were more likely to use manipulatives, when available. Further study is required to determine if gender differences are present based on treatment type.

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Bibliography

Ai, X. (2002). Gender differences in growth in mathematics achievement: Three-level longitudinal and multilevel analyses of individual, home, and school influences. *Mathematical Thinking and Learning* 4(1), 1-22.

Barke, H.-D. and T. Engida, (2001). *Structural Chemistry and Spatial Ability in Different Cultures.* Chemistry Education: Research and Practice in Europe, **2**(3): p. 227-239.
Bishop, J.E.(1978). Developing students spatial ability. *Science Teacher*, 45, 20-23.
Bennett, G.K., Seashore, H. G., & Wesman, A. G. (1973). *Differential aptitude tests, forms S and T.* New York: The Psychological Corporation.
Bodner, G.M. and T.L.B. McMillen, (1986). *Cognitive restructuring as an early stage in problem solving.* Journal of Research in Science Teaching, **23**: p. 727-37.
Casey, M.B., Pezaris, E., & Nuttall, R.L. (1992). Spatial ability as a predictor of math achievement: the important of sex and handedness patters, *Neuropsychologia, 30,* 35-40.
Carter, C.S., M.A. LaRussa, and G.M. Bodner, *A study of two measures of spatial ability as predictors of success in different levels of general chemistry.* Journal of Research in Science Teaching, 1987. **24**: p. 645-57.
CEEB Special Aptitude Test in Spatial Relations, developed by the College Entrance Examination Board, USA, (1939).
Coleman, S.L. and A.J. Gotch, (1998). *Spatial perception skills of chemistry students. use of the Inventory of Piaget's developmental tasks.* Journal of Chemical Education, **75**(2): p. 206-9.
Collins, *H. M (19*90) *Artificial experts: Social knowledge and intelligent machines.* Cambridge: MIT Press.
Deno, J. A. (1995). The relationship of previous experiences to spatial visualization ability. *Engineering Design Graphics Journal*, 59(3), 5-17.
Dreyfus, H. L. and Dreyfus, S. E. (1986) *Mind over Machine*. New York: Free Press.
Erickson, F & Gutierrez, K. (2002). Culture, rigor, and science in educational research. *Educational Researcher*, 31(8), 21-24.
Eyal, R. & Tendick, F. (2001). Spatial ability and learning the use of an angled laparoscope in a virtual environment. *Medicine Meets Virtual Reality* 2001,J. D. Westwood et al, Editors, IOS Press, Amsterdam, pp. 146-152.
Fennema, E., & Sherman, J.A. (1977). Sexual stereo-typing and mathematics learning. *The Arithmetic Teacher*, 24(5), 369-372.
Gimmestad, B. J. (1989). Gender differences in spatial visualization and predictors of success in an engineering design course. *Proceedings of the National Conference on Women in Mathematics and the Sciences*, St. Cloud, MN, 133-136.
Guay, R. B. (1977). Purdue spatial visualization test: Rotations. West Lafayette, IN, Purdue Research Foundation.
Hungwe, K.N. (1999) Becoming a machinist in a changing industry. Unpublished doctoral dissertation. Michigan State University.
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) 151-158.
Hier, D.B., & Crowley, Jr., W.F. (1982). Spatial ability in androgen-deficient men. New England Journal of Medicine, 306(20), 1202-1205.
Jones, E. E., Farina, A., Hastorf, A.H., Markus, H., Miller, D. T., & Scott, R. (1984). *Social Stigma: the psychology of marked relationships*. New York: Freeman.
Leopold C., Sorby, S. & Gorska, R. (1996). Gender differences in 3-D visualization skills of engineering students. *Proceedings of the 7th International Conference on Engineering Computer Graphics and Descriptive Geometry*, Andrzej Wyzykowski, et. al., Editors, Cracow, Poland, 560-564.
Linn, M.C. & Petersen, A.C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development,* 56, 1479-1498.
Maier, P. H. (1994). Raeumliches vorstellungsvermoegen. Frankfurt a.M., Berlin, Bern, New York, Paris, Wien: Lang.
Mc Kim, R. H. (1980). **experiences in visual thinking**, PWS Publishers, Boston Massachusetts.
Medina, A. C., Gerson, H. B. P., & Sorby, S. A. (1998). Identifying gender differences in the 3-D visualization skills of engineering students in Brazil and in the United States. *Proceedings of the International Conference for Engineering Education 1998*, Rio de Janeiro, Brazil.
National Council of Teachers of Mathematics (2000). Principles and Standards for School Mathematics

Norman, K.L. (1994). Spatial visualization-A gateway to computer-based technology. *Journal of Special Educational Technology*, XII(3), 195-206.
Pribyl, J.R. and G.M. Bodner, (1987). *Spatial ability and its role in organic chemistry: a study of four organic courses.* Journal of Research in Science Teaching, **24**: p. 229-40.
Small, M.Y. and M.E. Morton, (1983). *Spatial visualization training improves performance in organic chemistry.* Journal of College Science Teaching, **13**(1983): p. 41-3.
Smith, I. M. (1964). Spatial ability-Its educational and social significance. London: University of London.
Sorby, S. A. (2000). Spatial abilities and their relationship to effective learning of 3-D modeling software. *Engineering Design Graphics Journal*, 64(3), 30-35.
Spencer, S. J., Steele, C.M., & Quinn, D., (1999). Stereotype threat and women's math performance. *Journal of Experimental Social Psychology, 35,* 4-28.
Stafford, R.E. (1972). Hereditary and environmental components of quantitative reasoning. *Review of Educational Research,* 42, 183-201.
Steele, C. M., James, J.B. & Chait Barnett, R. (2002). Learning in a man's world: examining perceptions of undergraduate women in male-dominated academic areas. *Psychology of Women Quarterly, 26,* 46-50.
Tartre, L.A. (1990). Spatial skills, gender, and mathematics. In E. H. Fennema & G. C. Leder (Eds.), *Mathematics and Gender,* (pp. 27-59). New York, NY: Teachers College Press
Vandenberg, S. G., & Kuse, A.R. (1978). Mental rotations, a group test of three dimensional spatial visualization. *Perceptual and Motor Skills, 47*, 599-604.
Yang, E.-m., T. Andre, and T.J. Greenbowe, *Spatial ability and the impact of visualization/animation on learning electrochemistry.* International Journal of Science Education, 2003. **25**(3): p. 329-49.

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