Developing 3D spatial skills for engineering students *

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SUMMARY: *Researchers have found that 3D spatial skills are critical to success in a variety of careers, particularly in engineering and science. For engineering, the ability to mentally rotate objects in space has been found to be of particular importance. Unfortunately, of all areas of cognition, 3D spatial skills still exhibit some of the most robust gender differences favouring males, and the most pronounced gender differences are in the area of mental rotations. For this reason, poorly developed 3D spatial skills could be a hindrance to the success of women in engineering. University educators are quick to recognise deficiencies in math and chemistry, and many US universities have developed remediation programs for students with weaknesses in these areas. At a time when we are actively recruiting women for engineering programs, however, it is important to consider all possible barriers to their success. At Michigan Technological University (MTU), we have been offering a special course aimed at improving the 3D spatial skills of engineering students, particularly women, since 1993. This paper will summarise the findings obtained over the past decade at MTU in improving the 3D spatial skills of engineering students. The paper will also feature improvements in student success that we have achieved, especially for women, through implementation of this bridging course.*

1 BACKGROUND

The ability to visualise 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. 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 favouring males, especially in the ability to mentally rotate three-dimensional (3D) objects. This has obvious implications for our attempts to encourage gender equity in technical and scientific fields. Recognising the importance of well-developed spatial skills for technological careers, the National Council of Teachers of Mathematics (NCTM) in the US 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.

2 PRIOR RESEARCH IN SPATIAL COGNITION

According to Piaget (Bishop, 1978), spatial skills are developed in three stages. In the first stage, topological skills are acquired. Topological skills are primarily two-dimensional (2D) and are acquired by most children by the age of 3-5. With these skills, children are able to recognise an object's closeness to others, its order in a group, and its isolation or enclosure by a larger environment. The second stage involves visualising 3D 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 visualising at this stage of development. In the third stage, people are able to visualise the concepts of area, volume and distance in combination with those of translation, rotation

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and reflection. At this stage, therefore, a person is able to combine measurement concepts with their previously acquired projective skills.

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 visualisation 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 & 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 used 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 et al, 1992).

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 et al, 2003; Barke & Engida, 2001; Coleman & Gotch, 1998), subsequent work in the chemical sciences has been sparse and only Yang et al (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.

3 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 assertions 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 et al, 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 et al, 2002). This research suggests that female role models and mentors will be important to increasing gender diversity in science, technology, engineering and mathematics (STEM) disciplines. Therefore it is critically important to increase the number of women entering and completing degrees in STEM fields.

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 et al, 1996; Medina et al, 1998). Activities that require eye-to-hand coordination are particularly useful in developing these skills such as:

- playing with construction toys (eg. Lego) as a young child
- participating in classes such as shop, drafting or mechanics as a middle school or secondary student
- playing 3D computer games
- participating in certain types of sports
- having well-developed mathematical skills.

Since most of these factors typically have a fairly high degree of gender bias favouring men, it is no wonder that the spatial skills of women often fall behind those of their male peers.

In a meta-analysis of spatial studies, Linn & 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 visualising the whole object, and the analytic strategy uses a systematic, stepwise approach. The holistic strategy has been found to be more efficient (ie. less time consuming) in timed tests. Linn & Peterson have, therefore, concluded that "spatial strategy selection" is a factor in gender differences in mental rotation tasks. Hsi et al (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 visualisation 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 thfe overall development of learners.

4 ASSESSMENT OF SPATIAL SKILLS

Most spatial skills tests have been developed to assess a person's skill-levels in the first two stages of development. At the first stage of development, tests such as the Minnesota Paper Form Board (MPFB) (Likert, 1970) and the Group Embedded Figures (GEF) (Oltman et al, 1971) assess a person's topological spatial skills. These tests are essentially 2D tests and, as such, are not of significant interest to most engineering graphics educators.

At the second stage of development, there are numerous tests designed to assess a person's projective skill levels. Since these are 3D tests, a great deal of educational research has been conducted by engineering graphics educators using these instruments. The Mental Cutting Test (MCT) (CEEB, 1939) was first developed for a university entrance exam in the USA and consists of 25 items. For each problem on the exam, students are shown a criterion figure that is to be cut with an assumed plane. They must choose the resulting cross-section from among five alternatives. A sample problem from the MCT is shown in figure 1.

The Differential Aptitude Test: Space Relations (DAT:SR) (Bennett et al, 1973) consists of 50 items. The task is to choose the correct 3D object from four alternatives that would result from folding the given 2D pattern. In one study (Medina et al, 1998), it was found that a student's score on the DAT:SR was the most significant predictor of success in an engineering graphics course when compared to three other spatial visualisation tests given (including the MCT). A sample problem from the DAT:SR is shown in figure 2.

Several tests have been developed to assess a person's skill levels with regards to mental rotations. The Mental Rotation Test (MRT), developed by Vandenberg & Kuse (1978), is another standardised exam used to assess a person's skill in visualising rotated solids. The MRT was developed by Vandenberg & Kuse (1978) and it consists of 20 items. Each problem contains a criterion figure with two correct alternatives and two incorrect alternatives. Students are asked to identify which two of the alternatives are rotated images of the criterion figure.

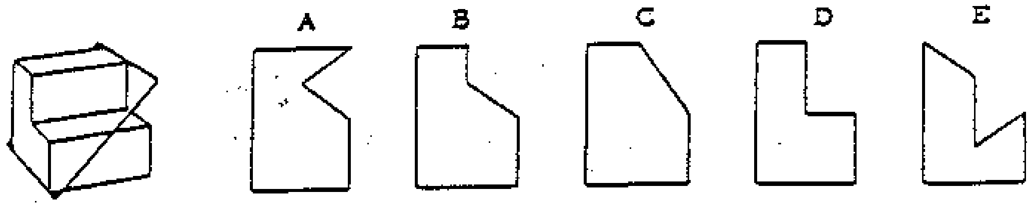

Figure 1: Sample problem from Mental Cutting Test.

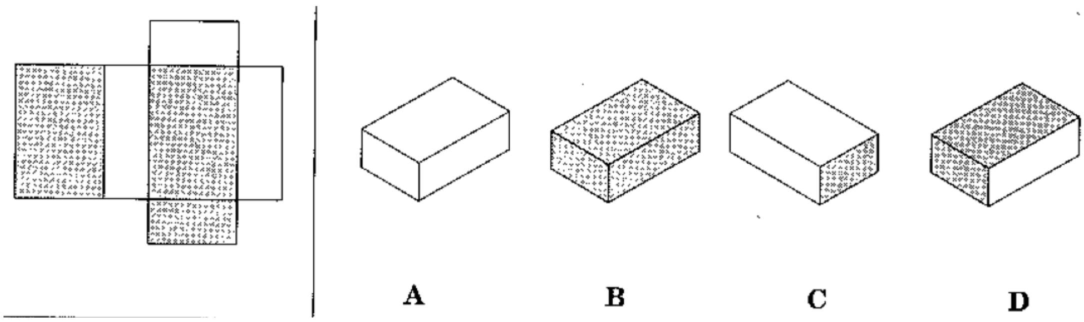

Figure 2: Sample problem from Differential Aptitude Test: Space Relations.

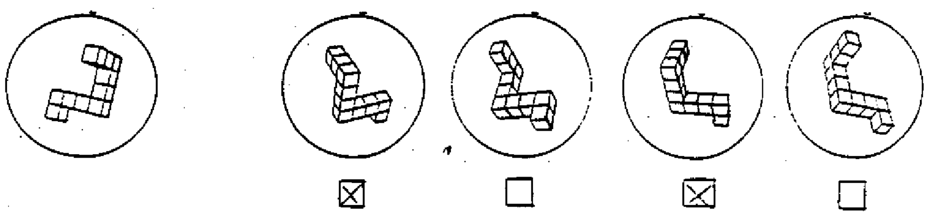

Figure 3: Sample problem from Mental Rotation Test.

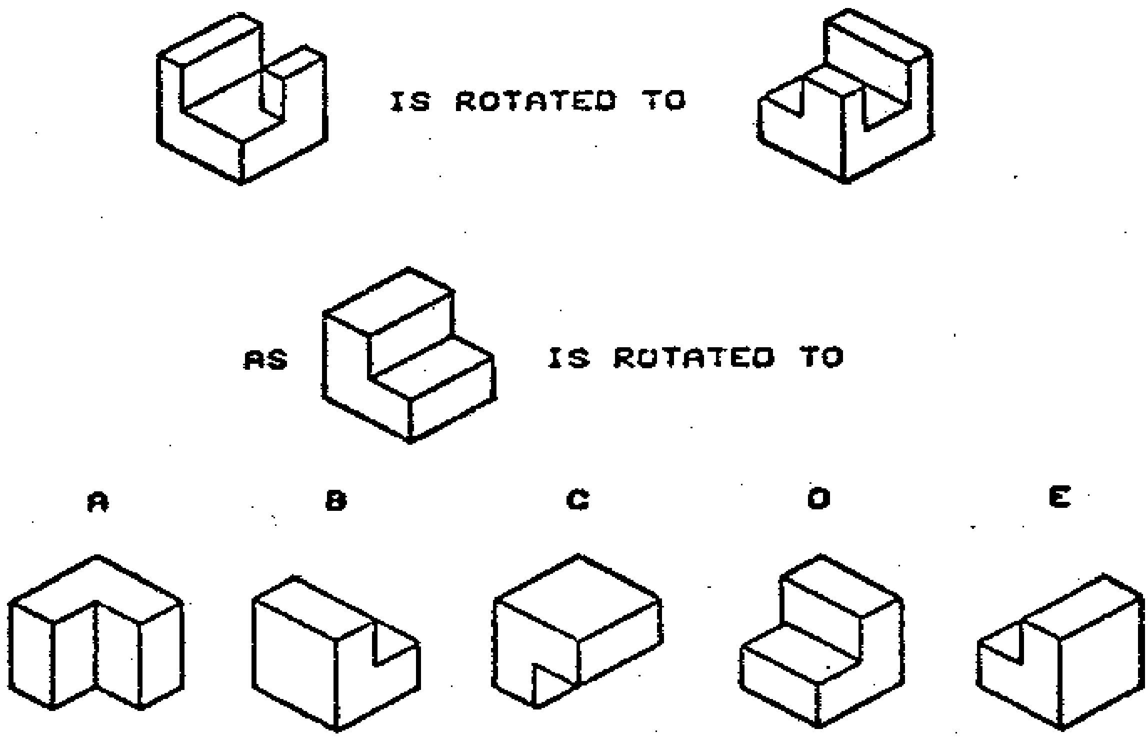

Figure 4: Sample problem from Purdue Spatial Visualization Test: Rotations.

An example problem from the MRT is shown in figure 3.

The Purdue Spatial Visualization Test: Rotations (PSVT:R) was developed by Guay (1977) and consists of 30 items. With this test, students are shown a criterion object and a view of the same object after undergoing a rotation in space. They are then shown a second object and asked to indicate what their view of that object would be if the second object were rotated by the same amount in space. In a previous research study at MTU, a student's score on the PSVT:R was determined to be the most significant predictor of success in an engineering graphics course of 11 variables tested (Gimmestad, 1989). In this study, the PSVT:R was the only spatial test given. Figure 4 shows an example problem from the PSVT:R.

5 SPATIAL SKILLS DEVELOPMENT AT MICHIGAN TECH

Gimmestad (now Baartmans) (1989) conducted a pilot study at Michigan Tech and found significant gender differences in spatial abilities as measured by a standardised testing instrument, the PSVT:R (Guay, 1977). She also found that a person's score on the PSVT:R was the most significant predictor of success in an engineering graphics course. Since design graphics courses are usually among the first courses in which first-year engineering students enrol, students who have poorly developed spatial skills, particularly women, may become discouraged and drop out of engineering altogether if they are struggling in their very first "engineering" course, while their male classmates seemingly breeze through the material.

Table 1: Failure and succeuss rates on PSVT:R.

	Male (n = 418)	Female (n = 117)
Perfect score on PSVT:R	42 (10.05%)	3 (2.56%)
Score of 60% or lower on PSVT:R	50 (11.96%)	46 (39.32%)

In 1993, Baartmans and Sorby wrote a proposal to the NSF that was funded. They developed a course and a textbook for enhancing 3D spatial skills for engineering students, particularly women. The course that was developed with these funds has been continuously offered at Michigan Tech since 1993. During freshman orientation in 1993 and in subsequent years, students who had declared majors of mechanical, civil, environmental, materials or general engineering were administered the PSVT:R. In the initial year, a total of 96 students failed the PSVT:R with a score of less than 60%. In examining the results from the PSVT:R for this initial group of students, the following observations were made. Although women made up only about 17% of the group taking the PSVT:R, they were about 43% of the group failing the test, making women nearly three times as likely to fail the PSVT:R than their male counterparts. Furthermore, of the 45 students who received perfect scores, only three were women. Failure and success rates for the men and women in this initial group are given in table 1. Gender differences in failure rates were significant ($p < 0.0001$) as were the gender differences for perfect scores ($p < 0.01$).

6 SPATIAL SKILLS COURSE

A random sample of 24 students was selected for participation in the experimental course and the remaining 72 students became the comparison group for the initial study conducted in 1993. The initial course (GN102) was offered for three credits (quarter system), and consisted of two hours of lecture and two hours of computer lab per week. In the lecture portion of the course, the topic for the day was introduced during the first 20-30 minutes of the hour. During the remainder of the session, students worked either individually or in groups to complete the activity sheet for the day with solutions to the problems discussed at the end of the session. Students were issued a set of snap cubes at the beginning of the course so that they could build objects to sketch from different angles and perspectives. In addition to the snap cubes, hand-held objects were used wherever feasible. The computer lab components used the solid modelling and visualisation capabilities of CAD software to demonstrate principles from the course. For example, when discussing object transformations, students were able to rotate a computer model of an object on the screen and see the effect of the operation. At the end of the course, the students were again administered the PSVT:R as part of their final exam. Gain scores for the students were computed and a dependent t-test showed that the gains were statistically significant ($p < 0.0001$).

After the initial course offering in 1993, Michigan Tech continued to offer GN102 each autumn. Each year, students were administered the PSVT:R during freshman orientation. Those students who failed the test were encouraged to enroll in our spatial skills course. Over the years we experienced varying degrees of cooperation with the academic advisors for the students, so not all of those who failed the exam enrolled in our course, however, a fair number of them did. During the lecture of the first day of each new class, students typically indicated that they were discouraged by the fact that they had failed the spatial skills test and we did our best to reassure them that there was "hope" for them. We discussed the importance of spatial skills for engineers and told them that it was likely that they had never had the prior opportunity to develop these skills and hence the purpose of the course. We continued to pre- and post-test with the PSVT:R during freshman orientation and the final exam. In each year, statistically significant gains were observed, with results presented in table 2.

7 LONG-TERM ASSESSMENT RESULTS

Between 1993 and 1998, a total of 536 students (285 men, 251 women) failed the PSVT:R at Michigan Tech during freshman orientation. The transcripts of

Table 2: Comparison of pre- and post-test results for GN102 (1993-98).

Test		1993 (n = 24)	1994 (n = 16)	1995 (n = 47)	1996 (n = 26)	1997 (n = 27)	1998 (n = 36)
PSVT:R	Average pre-test	51.7%	47.0%	54.6%	50.0%	48.3%	50.7%
	Average post-test	82.0%	79.3%	75.0%	81.7%	78.0%	72.7%
	Average gain	30.6%	32.3%	22.2%	31.4%	29.6%	21.8%
	Level of significance	($p < 0.0001$)	($p < 0.0005$)	($p < 0.005$)	($p < 0.0005$)	($p < 0.0005$)	($p < 0.0005$)

Table 3: Retention rates for men and women.

Male			Female	
Comparison group n = 200	Experimental group n = 85		Comparison group n = 161	Experimental group n = 90
62 (31.0%)	21 (24.7%)	Not retained	51 (31.7%)	10 (11.1%)
34 (17.0%)	12 (14.1%)	Retained at Michigan Tech	33 (20.5%)	11 (12.2%)
104 (52.0%)	52 (61.2%)	Retained in engineering	77 (47.8%)	69 (76.7%)

all of these students were obtained in January 2000, and sorted into those who had failed the PSVT:R and enrolled in the course and those who failed the test and did not enroll in the course. In conducting the long-term assessment for the project, particular attention was paid to the attrition rate of the students in the comparison and experimental groups, and we were especially interested in determining the impact of this project on the retention of women in engineering. (In this case, students were considered to be "retained" if they were still enrolled in or had graduated from Michigan Tech.) The overall retention rates for this group of students for the project duration were computed and are presented in table 3. Statistical analysis reveals that the differences between retention rates for male students, although encouraging, were not significant, but that the difference in retention rates between the women in the comparison and experimental groups overall, and within the College of Engineering, specifically, was statistically significant ($p < 0.0002$ for each). (It should be noted that for the autumn 1993 randomly selected group of students, similar results were obtained, however, sample sizes for that group were not large enough to infer statistical significance.)

During the time that GN102 was offered, there were several different graphics courses that engineering students might take, depending on major. Table 4 presents the average grade point averages (GPAs) for the students in the comparison and experimental groups for a few graphics courses at Michigan Tech, as well as an overall GPA computed from all graphics courses taken by each group. As can be seen from this data, the students who had participated in the spatial skills course received better grades on average than those who did not.

It should be noted that, although the students in the experimental group were largely "self-selected", similar differences in grades were found for the autumn 1993 group where students were randomly selected for participation in the course. For this group of students, the graphics GPA for students in the experimental group was 3.03, compared to an average of 2.70 for students in the comparison group (Sorby & Baartmans, 2000). (Sample sizes for the 1993 group were not large enough to infer significance.)

8 MULTIMEDIA SOFTWARE DEVELOPMENT

In January 1998, we were awarded another grant from the NSF to replace the computer exercises that were developed as part of our initial funding (that were based on CAD software) with stand-alone multimedia software modules. Because we had received so many requests for this type of software over the years, this seemed to be the logical "next step" in the project. Our goal was to develop a series of nine multimedia modules that could be used either as stand-alone entities or as a supplement to the text we had written. Along with this software, we developed a workbook with problems similar to those we had found to be helpful in developing spatial skills. In designing the software and workbook modules, special care was taken to ensure that they would be useful for a diverse audience. This project resulted in a set of user-friendly and gender-neutral materials that was published by Delmar Learning in July 2002. The software modules, included as a CD-ROM in the back of the workbook, are stand-alone and work with either a Mac or PC.

With the development of the multimedia software and workbook, the spatial skills course at Michigan Tech was modified significantly beginning in the autumn of 2000. Since the new software and workbook are self-contained, students can now work through the exercises in a somewhat self-paced manner, with little instruction from the teacher. In the current version of our spatial skills course, students attend a two-hour session each week of the semester and first work through the multimedia module assigned for the week. They then complete various exercises from the workbook to turn in at the end of the session. Thus, what was once a labour-intensive course (from a faculty member's standpoint) has now become merely a supervised lab setting that can be staffed by an upper-level undergraduate student who is familiar with the excercises.

Table 4: Average GPAs in subsequent graphics courses.

	Comparison group	Experimental group	Significance of the difference in means
ME104 – Engineering Spatial Analysis	2.30 (n = 126)	2.79 (n = 74)	$p < 0.0005$
GN135 – Introduction to Computer Aided Design	3.02 (n = 26)	3.31 (n = 24)	N.S.
Overall	2.61 (n = 406)	2.93 (n = 237)	$p < 0.0001$

Table 5 presents data gathered comparing gains in spatial skills achieved by students in the previous version of our spatial skills course with those obtained in the newer version of the course where students merely work through the modules individually with very little direct instruction. The data presented in this table stems from a number of spatial skills tests administered both pre- and post-course. The tests, each designed to assess a different spatial skills component, include the PSVT:R, DAT:SR, MCT and MRT.

From the data presented in table 5, it is apparent that students using the multimedia software and workbook are improving their spatial skills, as well as those who participated in our traditional lecture/lab course.

Data was also recently gathered regarding student performance in introductory courses taken by all engineering students. For this study, student transcripts were obtained for those who failed the PSVT:R during freshman orientation for 2000, 2001 and 2002. The transcripts were sorted into those who had participated in the course featuring the multimedia software (EG) and those who had not participated in the course (CG). Grades for several courses were examined – Calculus I, Chemistry I,

Table 5: Pre- and post-course spatial results.

Spatial Test	Traditional spatial skills course (n = 186)		"Self-paced" multimedia course (n = 61)	
	Average pre-score (% correct)	Average post-score (% correct)	Average pre-score (% correct)	Average post-score (% correct)
PSVT:R	50.9%	77.0%	49.0%	73.3%
DAT:SR	62.3%	78.3%	57.6%	77.0%
MCT	37.9%	51.4%	34.4%	50.4%
MRT	61.9%	71.9%	53.0%	72.8%

Table 6: Average GPAs for selected introductory courses.

Course	Male		Female	
	CG (n = 120)	EG (n = 82)	CG (n = 53)	EG (n = 87)
Engineering I	2.53	2.90	2.84	3.16
Calculus I	2.26	2.51	2.52	3.07
Chemistry I	2.49	2.54	2.72	2.86
Engineering II	2.69	2.93	2.74	2.95
Physics I	2.04	2.15	1.97	2.34
Overall	2.58	2.87	2.78	3.13

Table 7: Retention rates for men and women from multimedia course.

Male			Female	
CG n = 120	EG n = 82		CG n = 53	EG n = 87
36 (30.0%)	19 (23.2%)	Not retained	15 (28.3%)	11 (12.6%)
84 (70.0%)	63 (76.8%)	Retained at Michigan Tech	38 (71.7%)	76 (87.4%)

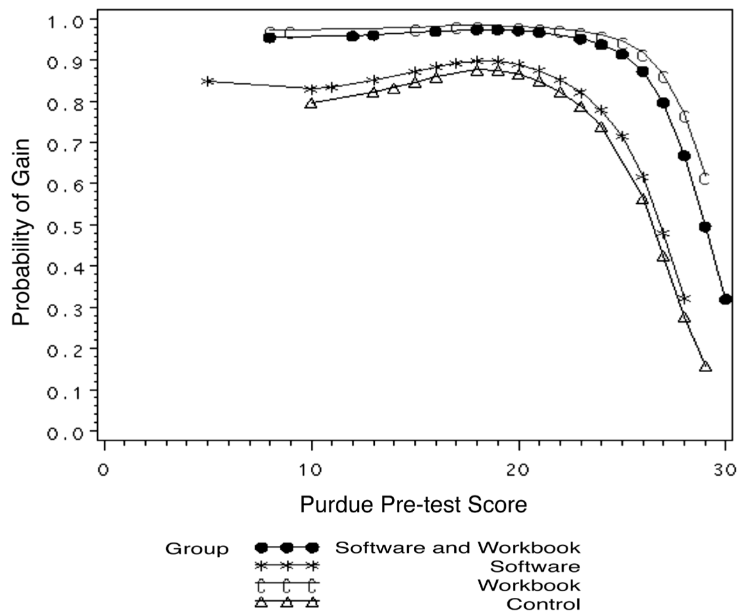

Figure 5: Fitted logistic regression models for the four groups.

Physics I, and Engineering I and II. Overall GPAs were also examined for these students. Table 6 presents the average GPAs obtained from this study for both the CG and EG by gender.

The data presented in table 6 shows that the students who participated in the course featuring the multimedia software performed better on average in various introductory courses than did their counterparts who had not. This is especially true for the female students. Because these students were all self-selected, it is impossible to determine if the improvement in student performance is due only to the spatial skills intervention.

Retention data was also examined for this group of students and similar findings were obtained when compared to the previous version of the course. Table 7 contains retention data for the students enrolled in the course that used multimedia software. Differences in retention rates for male students were not significant; however, differences in retention rates for women were significant (p = 0.01).

9 ASSESSMENT OF MEDIA SOFTWARE AND WORKBOOK MATERIALS

The multimedia software and workbook have been evaluated extensively over the years. Some of the assessments include attitudinal surveys of user-friendliness and usability of the software in the formative stages and comparisons of student performance on standard test questions between those who had used the software/workbook with those who had not (Gerson et al, 2001). In a recent study of the effectiveness of the multimedia software/workbook, volunteers were identified from students at Michigan Tech who were not first-year engineering students. Approximately 160 students participated in the study and they were randomly assigned to one of four groups, making sure to keep a balance between factors such as gender and initial PSVT:R score. The first group went through the spatial training over a period of 10 weeks using the software only. The second group used only the workbook during the training sessions and the third group used both the software and the workbook. The fourth group constituted the comparison group for the study. The comparison group underwent no spatial skills training. All four groups were administered the PSVT:R as a post-test. The data from this analysis was analysed using a Logistic Regression Model, with the results presented in figure 5.

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. These findings seem to support similar findings from previous studies that showed that sketching is important to the development of 3D spatial skills (Sorby & Gorska, 1998). 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.

10 CONCLUSIONS

We know that engineering has many "gateway" courses. Typically, these are thought to be calculus, chemistry or physics. From the results of this project, it seems that for women, and for some men, engineering graphics may be a significant gateway course due to poorly developed 3D spatial skills. By developing and implementing a course to help students improve their ability to visualise in three dimensions, Michigan Tech was able to improve retention rates in engineering, particularly for women. Further efforts to use multimedia software in conjunction with a workbook in an instructional setting have been shown to have a similar positive impact on developing 3D spatial skills, on improving grades in follow-on courses and on improving retention rates.

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REFERENCES

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,* Vol. 4, No. 1, pp. 1-22.

Barke, H. D. & Engida, T. 2001, "Structural chemistry and spatial ability in different cultures", *Chemistry Education: Research and Practice in Europe,* Vol. 2, No. 3, pp. 227-239.

Bennett, G. K., Seashore, H. G. & Wesman, A. G. 1973, *Differential aptitude tests, forms S and T,* The Psychological Corporation, New York.

Bishop, J. E. 1978, "Developing students spatial ability", *Science Teacher,* Vol. 45, pp. 20-23.

Bodner, G. M. & McMillen, T. L. B. 1986, "Cognitive restructuring as an early stage in problem solving", *Journal of Research in Science Teaching*, Vol. 23, pp. 727-37.

Carter, C. S., LaRussa, M. A. & Bodner, G. M. 1987, "A study of two measures of spatial ability as predictors of success in different levels of general chemistry", *Journal of Research in Science Teaching,* Vol. 24, pp. 645-57.

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,* Vol. 30, pp. 35-40.

Coleman, S. L. & Gotch, A. J. 1998, "Spatial perception skills of chemistry students. use of the Inventory of Piaget's developmental tasks", *Journal of Chemical Education,* Vol. 75, No. 2, pp. 206-9.

College Entrance Examination Board, 1939, *CEEB Special Aptitude Test in Spatial Relations,* USA.

Deno, J. A. 1995, "The relationship of previous experiences to spatial visualization ability", *Engineering Design Graphics Journal,* Vol. 59, No. 3, pp. 5-17.

Dreyfus, H. L. & Dreyfus, S. E. 1986, *Mind over Machine,* Free Press, New York.

Eyal, R. & Tendick, F. 2001, "Spatial ability and learning the use of an angled laparoscope in a virtual environment", *Medicine Meets Virtual Reality,* Westwood, J. D. (editors), IOS Press, Amsterdam, pp. 146-152.

Fennema, E. & Sherman, J. A. 1977, "Sexual stereotyping and mathematics learning", *The Arithmetic Teacher,* Vol. 24, No. 5, pp. 369-372.

Gerson, H. B. P., Sorby, S. A., Wysocki, A. & Baartmans, B. J. 2001, "The Development and Assessment of Multimedia Software for Improving 3-D Spatial Visualization Skills", *Computer Applications in Engineering Education,* Vol. 9, No. 2, pp. 105-113.

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, pp. 133-136.

Guay, R. B. 1977, *Purdue spatial visualization test: Rotations,* Purdue Research Foundation, West Lafayette, IN.

Hier, D. B. & Crowley Jr., W. F. 1982, "Spatial ability in androgen-deficient men", *New England Journal of Medicine,* Vol. 306, No. 20, pp. 1202-1205.

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,* Vol. 86, No. 2, pp. 151-158.

Hungwe, K. N. 1999, "Becoming a machinist in a changing industry", Unpublished doctoral dissertation, Michigan State University.

Jones, E. E., Farina, A., Hastorf, A. H., Markus, H., Miller, D. T. & Scott, R. 1984, *Social Stigma: the psychology of marked relationships,* Freeman, New York.

Likert, R. 1970, *The Revised Minnesota Paper Form Board Test Manual,* The Psychological Corporation, New York.

Linn, M. C. & Petersen, A. C. 1985, "Emergence and characterization of sex differences in spatial ability: A meta-analysis", *Child Development*, Vol. 56, pp. 1479-1498.

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,* Wyzykowski, A., et. al. (editors), Cracow, Poland, pp. 560-564.

Maier, P. H. 1994, *Raeumliches vorstellungsvermoegen*, Lang, Frankfurt a.M., Berlin, Bern, New York, Paris, Wien.

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,* Vol. XII, No. 3, pp. 195-206.

Oltman, P. K., Raskin, E. & Witkin, H. A. 1971, *Group Embedded Figures Test,* Consulting Psychologists Press, Palo Alto.

Pribyl, J. R. & Bodner, G. M. 1987, "Spatial ability and its role in organic chemistry: a study of four organic courses", *Journal of Research in Science Teaching,* Vol. 24, pp. 229-40.

Smith, I. M. 1964, *Spatial ability – Its educational and social significance,* University of London, London.

Sorby, S. A. 2000, "Spatial abilities and their relationship to effective learning of 3-D modeling software", *Engineering Design Graphics Journal,* Vol. 64, No. 3, pp. 30-35.

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,* Vol. 89, No. 3, pp.301-307.

Sorby, S. A. & Gorska, R. 1998, "The Effect of Various Courses and Teaching Methods on the Improvement of Spatial Ability", *Proceedings of the 8th International Conference on Engineering Design Graphics and Descriptive Geometry,* Austin, TX, pp.252-256.

Spencer, S. J., Steele, C. M. & Quinn, D. 1999, "Stereotype threat and women's math performance", *Journal of Experimental Social Psychology,* Vol. 35, pp. 4-28.

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,* Vol. 26, pp. 46-50.

Tartre, L. A. 1990, "Spatial skills, gender, and mathematics", In *Mathematics and Gender,* Fennema, E. H. & Leder, G. C. (editors), Teachers College Press, New York, NY, pp. 27-59.

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

Yang, E. M., Andre, T. & Greenbowe, T. J. 2003, "Spatial ability and the impact of visualization/animation on learning electrochemistry", *International Journal of Science Education,* Vol. 25, No. 3, pp. 329-49.

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