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RESEARCH REPORT

Educational Research in Developing 3-D Spatial Skills for Engineering Students

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The ability to visualize in three dimensions is a cognitive skill that has been shown to be important for success in engineering and other technological fields. For engineering, the ability to mentally rotate 3-D objects is especially important. Unfortunately, of all the cognitive skills, 3-D rotation abilities exhibit robust gender differences, favoring males. The assessment of 3-D spatial skills and associated gender differences has been a topic of educational research for nearly a century; however, a great deal of the previous work has been aimed at merely identifying differences. The author has been conducting applied research in the area of spatial skills development for more than a decade aimed at identifying practical methods for improving 3-D spatial skills, especially for women engineering students. This paper details the significant findings obtained over the past several years through this research and identifies strategies that appear to be effective in developing 3-D spatial skills and in contributing to student success.

Keywords: *Engineering education; Spatial skills; Gender differences; Spatial training; Student success*

Background

Prior to the 1950s, engineering was primarily an apprenticeship-like profession. Engineering curricula stressed practical, hands-on topcis such as drafting, machining, surveying, and other types of fieldwork. In the post-Sputnik era, science and mathematics began to play a much more significant role in engineering education to the point where most engineering programs are now required by ABET (the engineering accrediting society in the USA) to include 25% of their total credits in

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college-level mathematics and science courses. Most engineering students complete two to three semesters of calculus, two semesters of physics, one to two semesters of chemistry, differential equations, and statistics. Further, as the frontiers of knowledge expand, the line between pure science and engineering has blurred significantly. In emerging fields such as nanotechnology and biotechnology, the distinction between science and engineering has effectively been bridged such that scientists and engineers work side by side on projects that are advancing the human condition.

As a response to Sputnik, in the 1950s, a sweeping reform of engineering education was advocated by the now famous Grinter Report (ASEE, 1955). Regarding engineering graphics education, the Grinter Report included the following:

> Graphical expression is both a form of communication and a means for analysis and synthesis. The extent to which it is successful for these purposes is a measure of its professional usefulness. Its value as a skill alone does not justify its inclusion in a curriculum. The emphasis should be on spatial visualization, experience in creative thinking, and the ability to convey ideas, especially by free-hand sketching, which is the normal mode of expression in the initial stages of creative work. (p. 16)

Although this report was written more than a half-century ago, its comments regarding engineering graphics education still ring true today.

Ferguson (1992) points out that the very first engineers started as artists during the Renaissance. Early engineers such as Francesco di Giorgio, Leonardo da Vinci, Georg Agricola, and Mariano Taccola were artists first and engineers second. Ferguson also asserts that engineering drawing and descriptive geometry were actually developed in parallel and agrees with Yves Deforge, author of a French history of technical drawing, that "technical drawing is not the child of descriptive geometry." Ferguson also claims that the engineering education of today has diverged too much from its artistic, visual beginnings, and that our curriculum relies too heavily on analytical methods and not enough on tactile and visual perception. He maintains that many of the well-publicized engineering failures in the recent past (including the Challenger explosion, the Hubble space telescope, the Tacoma Narrows Bridge, and the USS Vincennes Aegis system among others) occurred largely because of the elimination of visual, tactile, and sensory aspects from the engineering curriculum of today.

Spatial skills have been a significant area of research in educational psychology since the 1920s or 1930s. In his "A Plea for Visual Thinking," Arnheim (1986) asserts that most educational psychologists erroneously believe that there is a distinct dichotomy between perception (visual thinking) and reasoning (cognitive thinking). He states that as far back as Descartes, the reasoning abilities of humans were considered to be superior to their perceiving abilities. Arnheim argues that perception and reasoning are both necessary in the thinking process and that to elevate the reasoning thinking skills above the visual thinking skills is to ignore the way the mind actually works. In fact, he believes, that "Thinking, then, is mostly visual thinking."

The downgrading of the value of visual thinking, dating back to Descartes, has persisted in our culture such that the only skills of value in our current educational system are the verbal and analytical. Sommer (1978) points out that our educational system is to blame for the lack of emphasis on visualization and visual thinking skills. He asserts:

> School more than any other institution, is responsible for the downgrading of visual thinking. Most educators are not only disinterested in visualization, they are hostile toward it. They regard it as childish, primitive, and prelogical. Classes in mechanical drawing, shop and the arts, in which spatial thinking still plays a role, are considered second-rate intellectual activities. (Sommer, 1978, p. 54)

Development and Assessment of Spatial Skills

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 and are acquired by most children by the age of three to five. 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. Children who are able to put together puzzles have typically acquired this skill. In the second stage of development, children have acquired projective spatial ability. This second stage involves visualizing 3-D 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 for objects that they are familiar with from their everyday life experiences. If the object is unfamiliar many students in high school or even college have difficulty in visualizing at this stage of development. In the third stage of development, people are able to visualize the concepts of area, volume, distance, translation, rotation, and reflection. At this stage, a person is able to combine measurement concepts with their projective skills.

There are many theories as to why some students have highly developed spatial skills and others seem to be deficient in the development of these skills. However, there is a good deal of evidence to suggest that sketching 3-D objects is a significant factor in the development of these skills (Bowers & Evans, 1990; Field, 1994; McKim, 1980; Sorby & Baartmans, 1996; Sorby & Gorska, 1998). Several researchers have conducted studies to determine what type of pre-college activities tend to be present in those students who have well-developed spatial skills (Deno, 1995; Leopold, Sorby, & Gorska, 1996; Medina, Gerson, & Sorby, 1998). Although each study has produced slightly different results, it seems that activities that require eye-to-hand coordination are those that help to develop these skills. Factors that have been found to be significant for students with well-developed spatial skills include: (1) playing with construction toys as a young child; (2) participating in classes such as shop, drafting, or mechanics as a middle school or secondary student; (3) playing 3-D computer games; (4) participating in some types of sports; and (5) having well-developed mathematical skills.

Most spatial skills tests have been developed to assess a person's skill levels in the first two stages of development. At the second stage of development, there are numerous tests designed to assess a person's projective skill levels. Since these are 3-D tests, a great deal of educational research has been conducted by engineering graphics educators using these instruments.

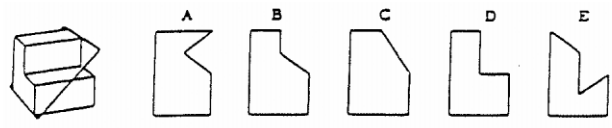

Figure 1. Sample problem from the MCT

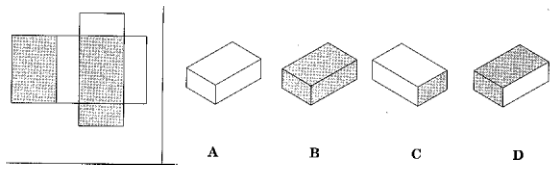

Figure 2. Sample problem from the DAT:SR

The Mental Cutting Test (MCT) 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 which is to be cut with an assumed plane. They must choose the correct 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, Seashore, & Wesman, 1973) consists of 50 items. The task is to choose the correct 3-D object from four alternatives that would result from folding the given 2-D pattern. In one study, 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 visualization 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 regard to mental rotations. 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 Michigan Tech, 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, 1990). In this study, the PSVT:R was the only spatial test given. Figure 3 shows an example problem from the PSVT:R.

Gender Differences in 3-D Spatial Skills

It is well documented that the 3-D spatial visualization skills of women lag behind those of their male counterparts, especially for 3-D rotations (Linn & Petersen, 1985; Tartre, 1990; Voyer, Voyer, & Brydon, 1995). Theories for the cause of these differences include the assertion that spatial ability is related to a male sex hormone (Hier & Crowley, 1982) or that environmental factors are the primary reasons for

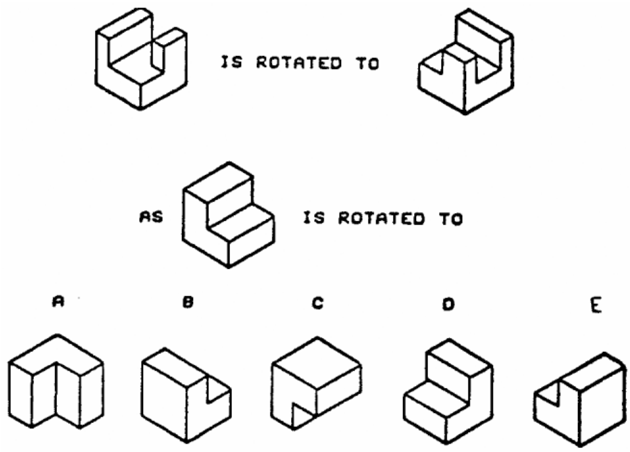

Figure 3. Sample problem from the PSVT:R

male–female differences in spatial skill levels (Fennema & Sherman, 1977). In research on which the author has collaborated (Leopold et al., 1996; Medina et al., 1998; Sorby & Baartmans, 1996) it was determined that, although men and women both have statistically significant gain scores through participation in graphics courses, the average post-test scores for women are lower than the average pre-test scores for men.

In 1993, the PSVT:R was administered to 535 first-year Michigan Tech engineering students during orientation. Of the 96 students who failed the test with a score of 60% or less, 43% were women, even though women were only 17% of the group taking the test. Thus, the women were three times more likely to fail the test than were their male counterparts. Furthermore, of the 45 students who earned a perfect score on the test, only 3 were women. Gender differences between failure and success rates on the test were statistically significant.

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 Petersen 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.

Spatial Skills in Science-Related Professions

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 (Bodner & McMillen, 1986; Carter, LaRussa, & Bodner, 1987; Pribyl & Bodner, 1987). 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. Recently, Yang, Andre, and Greenbowe (2003) 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 (Pribyl & Bodner, 1987; Small & Morton, 1983). 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 4 out of 60 cases. One might explain this lack of significance by considering the type of student taking organic chemistry, who tends 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 3-D 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 Hamlin, Boersma, and Sorby (2006) 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 that 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).

Research Rationale

Design graphics courses are among the first courses in which first-year engineering students enroll. For this reason, students who have poorly developed spatial skills, particularly women, may become discouraged and drop out of engineering altogether if they are struggling in their first engineering course while their classmates seemingly breeze through the material. This is especially discouraging as we strive to increase the number of women students who pursue engineering educations. For this reason, among others, the author, along with Baartmans, developed an introductory course aimed at improving the spatial skills of entering engineering students who have a demonstrated weakness in this area (Sorby & Baartmans, 1996), and it has undergone significant modifications and improvements over the years. The remainder of this paper describes the course in more detail and provides findings from associated research conducted by the author since 1993.

Spatial Skills Project: Initial course offering

In 1993 the author was co-investigator on a grant from the National Science Foundation (NSF) in the USA to develop a course aimed at first-year engineering students with weak 3-D visualization skills. During orientation students who had selected majors of mechanical, materials, civil, environmental, and general engineering were administered the PSVT:R. There were 535 students tested overall. Roughly 20% of the students (n = 96) failed the PSVT:R with a score of 60% or less. Women were approximately 17% of the group being tested, but were nearly half of the group failing the test. A random sample of 24 students was selected for participation in the pilot offering of the spatial skills course. The remaining 72 students who initially failed the PSVT:R and who were not selected for participation in the spatial course comprised the comparison group (CG).

At the time, Michigan Tech followed the quarter calendar and the spatial skills course was offered as a three-credit course over a 10-week period. There were two hours of lecture per week. During the lecture portion of the course, students were presented with the topic for the day and then worked individually to complete three to four in-class exercises. Correct answers to the in-class problems were presented to the group as a whole. A 2 hour computer lab complemented the lecture each week. The computer lab utilized solid modeling CAD software to illustrate the principles presented during lecture.

With the NSF funding, a textbook was written that was eventually published by Prentice Hall (Baartmans & Sorby, 1995). The topics in the new course and in the text were organized in an order that was thought to develop 3-D spatial skills. The topics included:

- Sketching isometric pictorials from coded plans
- Sketching multi-view drawings of simple objects
- 2-D to 3-D transformations—paper folding
- 3-D coordinate systems
- Object transformations including translation, scaling, rotation, and reflection
- Cross-sections of solids
- Surfaces and solids of revolution
- Combining objects by cutting, joining, or intersecting

Table 1. PSVT:R pre- and post-test scores in percentage

Year	1993	1994	1995	1996	1997	1998	Overall
Sample size (n)	24	16	47	26	27	36	186
Pre-test (%)	51.7	48.0	54.7	50.0	48.3	50.7	50.5
Post-test (%)	82.0	79.3	75.0	81.7	78.0	72.7	76.9
Gain (%)	30.3	31.3	20.3	31.7	29.7	22.0	26.4
Sig. of Gain	$p < 0.0001$	$p < 0.0005$	$p < 0.005$	$p < 0.0005$	$p < 0.0005$	$p < 0.0005$	$p < 0.0001$

At the end of the quarter, students were administered the PSVT:R as part of their final exam for the course. Students demonstrated statistically significant gains on the test with an average pre-test score of 51.7% and an average post-test score of 82.0%.

From 1994–1998, the spatial skills course was conducted in much the same way that it had been offered initially. Each year, first-year engineering students were tested during orientation with the PSVT:R. Students who failed the test were encouraged to enroll in the spatial skills course. Some chose to do so; others did not. Statistically significant gains on the PSVT:R were observed for each offering of the course. It should be noted that even though the course was aimed primarily at helping women engineering students develop their 3-D spatial skills, that men who initially failed the PSVT:R were also invited to join the course. The techniques used in the course were equally effective in improving the 3-D spatial skills of men as they were with women such that no gender differences in average pre- or post-test scores were observed in any year. (Recall that the students enrolled in the course had initially failed the PSVT:R and were thus not a representative sample of the population in general.) Table 1 includes pre- and post-test scores for each year through 1998, with the shading in Column 1 indicating that this sample was randomly selected.

The data in Table 1 shows that statistically significant gains were achieved in each year that the initial course was offered. The data also indicates that the gains for the randomly selected group were similar to the gains achieved by the self-selected students.

Spatial Skills Project: Multimedia software development

In 1998, a second grant was obtained from the NSF to create multimedia software and a workbook to replace the text and CAD-based computer exercises developed previously. In all, nine modules were developed with workbook modules complementing software modules and vice versa. The software and the workbook were developed to be stand-alone products if desired. The nine modules were:

- Isometric pictorials from coded plans
- Multi-view drawings
- Paper folding/2-D to 3-D transformations
- Object rotations about one axis

- Object rotations about two or more axes
- Object reflections and symmetry
- Cutting planes and cross-sections
- Surfaces and solids of revolution
- Combining solids

The materials were developed over the 1998–2000 timeframe and were published by Thomson-Delmar Learning (Sorby & Wysocki, 2003). The multimedia software was evaluated through attitudinal surveys with the first-year engineering students in formative and summative assessments. Students were asked to rate the software on a one to four scale regarding ease of use and ease of understanding. Each module received a rating of around 3.5 to 3.7 on the four-point scale, indicating that the students thought the multimedia software was an effective tool for learning the course topics.

For the 1998 offering of the spatial skills course, the multimedia software replaced the CAD exercises for four of the nine lab sessions, with the lectures conducted as they had been done previously. For the 1999 offering of the spatial skills course, students who failed the PSVT:R were given the option of choosing the traditional three-credit course or enrolling in a special topics one-credit course. The three-credit course met for two hours of lecture each week and one 2 hour computer lab that utilized the multimedia software in place of the CAD exercises. The lectures were conducted the way they had been for the previous six years. The one-credit special topics course met for a two hour lab session each week where students were given no formal instruction but worked with the multimedia software module for the start of the session and then completed the workbook exercises for the remainder of the time.

Performance on common quiz questions was compared between students in the traditional course and those in the special topics course. On the first of these quizzes, students in each course performed virtually identically. Average scores were the same and similar mistakes were made by each of the groups. For the second quiz, students in the special topics course actually outperformed students in the traditional course. For example, for one set of problems (covering paper folding) on the second quiz, 90% of the students in the special topics course answered all three of the questions correctly; whereas, only 15% of the students in the traditional course answered the three questions correctly. For a different set of problems (covering object rotations), nearly 100% of the students in the special topics course answered the questions correctly, compared to only 35% of the students in the traditional course. The instructors of the courses theorized that one reason the students in the special topics course outperformed students in the traditional course on the quiz was likely due to the fact that the students in the special topics course actually spent a great deal of time sketching objects as they completed the workbook pages. From previous research conducted by the author, it was shown that sketching 3-D objects greatly enhances spatial skills (Sorby & Gorska, 1998).

Students in the traditional and special topics courses were also administered the PSVT:R as a pre- and post-test. Gain scores on the test were virtually identical for both groups—a gain of 22.1% for the students in the traditional course and a gain of 23.0% in the special topics course.

Spatial Skills Project: Revised course offering

In the fall of 2000, Michigan Tech made the calendar conversion from three 10-week quarters to two 14-week semesters during an academic year. This move necessitated a curriculum overhaul. As a result of the semester conversion, a common first year was also adopted at Michigan Tech, meaning that *all* engineering students were now administered the PSVT:R during orientation and not just those in selected majors. Based on the results from testing with the multimedia software, the spatial skills course was reconstituted as a one-credit course that meets for one 2 hour lab session per week. For the revised course, the faculty member delivers a 10 to 15 minute mini-lecture at the beginning of the session introducing the topic for the day. Students then work in pairs to complete the corresponding multimedia software module. For the remainder of the session, students complete assigned pages from the workbook, either in pairs or individually.

There are nine software/workbook modules and 14 weeks in a semester. The remaining sessions are spent on pre- and post-testing (two sessions), quizzes (two sessions), and one additional session on multi-view drawing with inclined surfaces. The session on inclined surfaces is taught in a traditional lecture mode with students completing multiple worksheets as an in-class exercise. The rationale for inclusion of this extra session on multi-view drawing is that this is an important topic in engineering graphics and the additional practice will benefit them in later courses.

Pre- and post-testing of the students in the multimedia software-based course were conducted and comparisons were made between the students in the revised semester course and the students in our initial quarter course. Test scores on the DAT:SR and the MCT were also included in this analysis. Table 2 includes the data from the pre- and post-testing.

The data presented in Table 2 shows that the students in the one-credit semester course, based on instruction with the multimedia software and the workbook, achieved similar gains on three different spatial skills instruments when compared to students in the traditional lecture-based three-credit spatial skills quarter course. In

Table 2. Pre- and post-test data for semester and quarter courses

	PSVT:R		MCT		DAT:SR	
	SEM	QTR	SEM	QTR	SEM	QTR
n	157	186	109	99	110	99
Pre-test (%)	48.3	50.5	34.8	37.9	62.1	62.3
Post-test (%)	73.7	76.9	52.6	51.4	77.9	78.3
Gain (%)	25.4	26.4	17.8	13.5	15.8	16.0
Sig. of Gain	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$

fact, it appears that the students in the semester course actually experienced *higher* gains on the MCT. This is likely due to the fact that the topic of cutting planes and cross-sections can be better illustrated with the multimedia software than it can be through lecture alone.

Spatial Skills Project: Testing materials with new audiences

In 2004, a new grant was obtained from the NSF with the goal of testing the multimedia software and the workbook developed previously with audiences other than first-year engineering students. The targeted audiences included undergraduate majors outside of engineering, high school students, and middle school students.

Study with Non-Engineering Undergraduates

In the first study, Michigan Tech first- and second-year students in majors other than engineering were invited to take the PSVT:R early in the fall semester of 2004. Students were given a $15 gift certificate to the college bookstore for completing the 20 minute test and a questionnaire. In all, approximately 160 students participated in the study. The students were majoring primarily in computer science or biology, with a few students from physics, chemistry, or technology. Student participants were randomly assigned to one of four groups based on PSVT:R score and gender. Three of the four groups participated in training with the educational materials over the remainder of the semester; the fourth group became the CG for the study and received no additional spatial skills training. The three experimental groups (EGs) attended weekly sessions, with one group using only the software, one group using only the workbook, and one group using both the software and the workbook for training purposes. At the end of the 10-week period, students who participated in the training exercises were post-tested with the PSVT:R. Students in the EGs were also administered the MCT as both a pre- and a post-test. At about the same time, students in the CG were invited to take the PSVT:R again. Table 3 includes the data obtained in this study.

Table 3. Pre- and post-test results from study with non-engineering students

	PSVT:R			MCT		
	Pre-test	Post-test	Gain	Pre-test	Post-test	Gain
EG software-only ($n = 34$)	70.1	79.4	9.3 ($p < 0.005$)	53.8	56.3	5.7 ($p < 0.05$)
EG workbook-only ($n = 34$)	75.6	87.4	11.9 ($p < 0.0001$)	53.8	61.3	7.5 ($p < 0.005$)
EG software and workbook ($n = 33$)	73.3	85.6	12.2 ($p < 0.0001$)	46.4	60.2	13.8 ($p < 0.0001$)
Comparison group ($n = 32$)	72.9	77.5	4.6 ($p < 0.1$)	NA	NA	NA

As illustrated by the data in Table 3, students in each of the EGs made significant gains in their spatial skills as measured by both the MCT and the PSVT:R. Students in the CG made marginally significant gains on the PSVT:R over roughly the same time period.

In further analyzing the pre- and post-test data from this study, a binary variable was created that equaled 1 if the student gained in score and equaled 0 if they had a negative or zero gain. A non-parametric logistic regression model was fitted to the data using this binary variable as the dependent variable with independent variables being group and pre-test 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 4 illustrates the results from this analysis.

In the logistic regression analysis, 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. This finding reinforces results from previous studies that showed the importance of sketching in developing 3-D spatial skills. The two groups that did participate in the sketching activities found in the workbook had significantly higher gains in spatial skills compared to those who did not. However, when the students who participated in the training activities were asked what their preferred treatment method was, 62% indicated that they would have liked to work with the software alone, in spite of the fact that this treatment method appears to be the least effective. The small gains exhibited by the students in the CG and in the software-only group could be due to either the practice effect in taking the PSVT:R

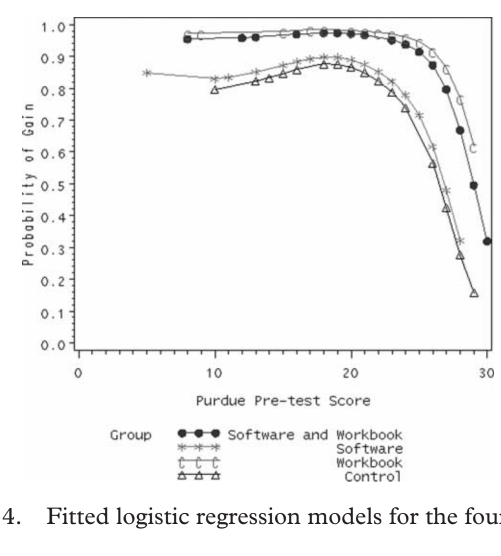

Figure 4. Fitted logistic regression models for the four groups

twice or they could be due to a natural improvement in spatial skills that most Michigan Tech students (who are all majoring in technological programs and who all enroll in high-level math courses) experience over the duration of a semester.

Studies with Middle and High School Students

A pilot study was conducted using the materials with middle school students in the spring of 2005. Students in the pilot middle school (grades seven and eight, ages 12–13) are required to take an Integrated Technology course that integrates the use of computers, graphing calculators, scientific probes, Geographic Information Systems, and Global Positioning Systems with their core courses in science, mathematics, social studies, and English. Of the 16 students in the pilot study, there were 12 females and 4 males. Typically, the students spent two to three days each week working on a module, with the remainder of the course time spent on other topics.

For each module, the teacher first previewed the module introduction from the workbook with the students and then observed and assisted them as they completed the computer tutorial. Students who finished the computer tutorial early started work on the workbook pages. Enough classroom time was allowed for the students to complete a majority of the workbook exercises in each module. As a result of limited access to computers, the students were grouped into pairs for the duration of the study. They worked in their partner pairs for both the computer and workbook exercises. The students were asked to evaluate each module upon completion through attitudinal surveys.

In analyzing the data obtained through the surveys, some interesting observations were made. The majority of the students felt that they understood the material and that they were given enough time to complete the exercises appropriately. Most students stated a preference for working with *both* the multimedia software and the workbook. This is in contrast to a similar question asked of the non-engineering university students who participated in the study in the fall of 2004. (The university students preferred to use the software alone for training purposes, even though it was the least effective mode for developing 3-D spatial skills.)

Students in the middle school pilot study were pre- and post-tested with a modified version of the PSVT:R. In this case, the test was modified to include only three choices per item to reduce the level of difficulty on the test for students at this age. (The test had been created and validated with older students.) Table 4 includes the results from testing with the modified instrument.

Table 4. Pre- and post-test results from pilot test with middle school students (n = 16)

	Pre-test (%)	Post-test (%)
High score	92.9	100
Low score	35.7	50.0
Mean	63.6	82.9
Standard deviation	17.9	12.1

Table 5. Pre- and post-test results for high school students

		PSVT:R	MCT	DAT:SR
Male	Avg. pre-test (%)	61.3	32.7	58.6
(n = 22)	Avg. post-test (%)	80.4	43.6	72.7
	Avg. gain (%)	19.1	10.9	14.1
Female	Avg. pre-test (%)	46.1	30.0	71.1
(n = 18)	Avg. post-test %)	64.4	37.2	80.0
	Avg. gain (%)	18.3	7.2	8.9

In performing statistical analysis on the data presented in Table 4, the average gain was 20.5% which was statistically significant ($p < 0.005$), even though the sample size was relatively small ($n = 16$). Thus, it appears that the software and workbook materials are effective in improving the 3-D spatial skills of the middle school students who participated in the study.

The software and workbook materials were also tested with a group of high school geometry students. In this case, the students completed the nine modules at the beginning of the academic year as a component of their regular mathematics instruction in a geometry course. Most of the students in the geometry class were in the tenth grade; however, there were a few students in ninth grade in the class. For this study, students were pre- and post-tested with a subset of 10 problems from each of the PSVT:R, the MCT, and the DAT:SR instruments. The items were chosen to be of varying difficulty, but were not modified in any way. Since gender differences were of particular interest in this study, pre- and post-test data were disaggregated and are presented in Table 5.

The data presented in Table 5 suggests that the software and workbook materials were effective in improving the 3-D spatial skills of the high school geometry students in a variety of components; however, the gender gap in skill level was not narrowed through this intervention on the PSVT:R; for the MCT, the gender gap may have worsened. On the DAT:SR the pre-test scores for females appeared to be higher than those for males; after the intervention the scores for males and females were closer than they had been. Statistical analysis of the results shows that only the gender differences on the PSVT:R were significant. Attitudinal surveys completed by the high school students also showed that they found the materials easy to use and to understand.

Spatial Skills Project: Longitudinal studies

Since 1993, several longitudinal studies have been conducted for students who participated in the spatial skills courses/training. The first of the longitudinal studies was conducted in ~1997. The subjects in this study were the participants in our initial offering of the course. For this study, EG1 was defined as those who failed the PSVT:R during orientation and enrolled in our course and the CG1 was defined as those who failed the PSVT:R and did not enroll in our course. It should be noted that for this particular study, the students in the EG were randomly chosen from the group who initially failed the PSVT:R.

The second and third longitudinal studies were conducted in 2000 and 2004, respectively. For these studies, students in the EGs were again those who had failed the PSVT:R and enrolled in the spatial skills course (EG2 and EG3); the CGs were made up of students who had failed the PSVT:R and not enrolled in the spatial skills course (CG2 and CG3). For the second longitudinal study (EG2 and CG2), the students enrolled or did not enroll in our original three-credit lecture-based quarter course between 1993 and 1998. (Thus, the students from the first longitudinal study were a small subset of the students in this longitudinal study.) For the third longitudinal study (EG3 and CG3), the students enrolled or did not enroll in our one-credit semester course that was based on the multimedia software and the workbook between 2000 and 2002. For both of these studies (except for the 1993 subset), the students were self-selected, i.e., all students who failed the PSVT:R were invited to enroll in the course but only a fraction of them did so.

The fourth longitudinal study was conducted in 2007. The subjects in this study were the non-engineering students who participated in our fall 2004 research project where the software and workbook materials were tested with audiences outside of engineering. For this study, recall that the students were randomly assigned to one of the four groups—comparison, software-only, workbook-only, or software and workbook. In this case, because the software-only group did not experience gains in spatial skills that were different from the gains experienced by the CG, those students were included with the CG for purposes of the longitudinal study. Therefore, EG4 was made up of students who initially failed the PSVT:R and participated in the training that was either based on the workbook-only or the software and workbook, and CG4 was made up of students who initially failed the PSVT:R and did not participate in the training activities or who participated in the software-only training sessions.

Table 6 summarizes the definitions of the EGs and CGs for the longitudinal studies.

Table 6. Longitudinal study groups

Study	Data period	Data collected	Randomly assigned	Experimental group	Comparison group
1	1993	1997	Yes	Failed PSVT:R. Enrolled in lecture course	Failed PSVT:R. Did not enroll in lecture course
2	1993–1998	2000	No	Failed PSVT:R. Enrolled in lecture course	Failed PSVT:R. Did not enroll in lecture course
3	2000–2002	2004	No	Failed PSVT:R. Enrolled in multimedia course	Failed PSVT:R. Did not enroll in multimedia course
4	2004	2007	Yes	Failed PSVT:R. Participated in training with workbook	Failed PSVT:R. Did not participate in training or participated in training with software only

For each of the longitudinal studies, transcripts of the students in the EGs and CGs were obtained during the data collection period. Since the project was ultimately focused on improving student success, the data collected from the transcripts included grades in subsequent courses. Whether or not the student had been retained (or had graduated) from Michigan Tech was also noted for each subject. Finally, since gender plays a large role in developing 3-D spatial skills, the gender of the subjects was also noted. It should also be noted that Study groups 1–3 were all engineering students; whereas, Study group 4 consisted of non-engineering students.

Grades in Follow-On Engineering Courses

Spatial skills have been shown to play a significant role in performance in engineering graphics and design courses. In fact, in research conducted by Gimmestad (1990), it was found that a person's score on the PSVT:R was the most significant predictor of success in engineering graphics of 11 variables examined. Prior to 2000, at Michigan Tech, engineering students targeted in our study enrolled in one or more graphics courses depending on their declared major. In most cases, these graphics courses were the first "engineering" courses that a student might take. With the development of the first-year engineering program commencing in the fall of 2000, all engineering students enrolled in two common courses—Engineering I and Engineering II. Graphics instruction was integrated throughout these new courses and no longer treated as a separate subject.

In analyzing the grade data, numerical values were assigned to the letter grades as follows: A = 4, AB = 3.5, B = 3, BC = 2.5, C = 2, CD = 1.5, D = 1, F = 0. When students took a course more than one time, the grade recorded was the first one that they received; subsequent grades for the same course were ignored. Average GPAs were computed for each group based on the number of students who enrolled in the respective courses. For longitudinal Studies 1 and 2, all graphics courses were grouped, since there was a wide variety in graphics courses available over those periods. Table 7 includes data on student performance in follow-on engineering/graphics courses for the students in Groups 1–3. The shading for the columns for Study group 1 indicates that these students were randomly assigned.

For the data presented in Table 7, differences in mean GPAs for engineering or engineering graphics courses for the students in Studies 2 and 3 were statistically significant. Differences for the GPAs earned by students in Study 1 were similar to

Table 7. Average GPAs in follow-on engineering courses

	EG1	CG1	EG2	CG2	EG3	CG3
Sample size (*n*)	19	44	237	406	169	173
Graphics/ Engineering I	3.03	2.70	2.93	2.61	3.04	2.62
Engineering II	—	—	—	—	2.94	2.71

those obtained in Studies 2 and 3, but were not statistically significant due in large part to the small sample sizes. Since the students in Study 1 were randomly assigned, this implies that the differences in Studies 2 and 3 were not due only to self-selection, and that the spatial skills training likely had a positive impact on student performance in follow-on engineering/graphics courses.

Grades in Other Follow-On Courses

Spatial skills have been linked to student success in a variety of science and technology courses. Grades in courses other than graphics were not examined for students in Study 1. For students in Study 2, only Calculus I grades were examined; however, for students in Studies 3 and 4, several science and mathematics grades were examined. The average GPAs in follow-on courses for the students in these studies are presented in Table 8. Once again, the shading in the columns reserved for Study 4 signifies that these students were randomly assigned.

For the data presented in Table 8, differences in average GPAs between EG3 and CG3 were statistically significant for all grades except that differences in Chemistry I GPAs were marginally significant. Differences in average GPAs between EG4 and CG4 for pre-calculus, chemistry, and computer science were marginally significant. All other differences between EG4 and CG4 were not significant; however, the sample sizes for this study were extremely small. It should be noted that EG4 included a significant number of physics majors (who were all in honors physics courses), which could account for the higher physics grades for that group.

From the data presented in Tables 7 and 8, there is some indication that success in science, mathematics, and engineering courses is improved through spatial skills training for students who initially exhibit weak skills as measured by the PSVT:R. Differences for randomly selected students are similar to those obtained for self-selected

Table 8. Average GPAs in follow-on science and mathematics courses

	EG2	CG2	EG3	CG3	EG4	CG4
Pre-calculus	—	—	—	—	3.00 ($n = 13$)	2.50 ($n = 23$)
Calculus I	2.38 ($n = 161$)	2.30 ($n = 300$)	2.78 ($n = 137$)	2.35 ($n = 128$)	3.12 ($n = 13$)	2.61 ($n = 27$)
Physics I	—	—	2.25 ($n = 126$)	2.02 ($n = 121$)	2.86 ($n = 14$)	3.13 ($n = 16$)
Chemistry I	—	—	2.70 ($n = 152$)	2.56 ($n = 144$)	3.18 ($n = 11$)	2.77 ($n = 24$)
Computer science I	—	—	—	—	3.45 ($n = 10$)	3.03 ($n = 32$)
Biology I	—	—	—	—	2.93 ($n = 7$)	3.31 ($n = 13$)
Overall GPA	—	—	3.00 ($n = 169$)	2.64 ($n = 173$)	3.12 ($n = 23$)	3.03 ($n = 32$)

students; however, sample sizes for the randomly selected groups were generally too small to infer statistical significance.

Retention Rates

As a final part of each longitudinal study, retention rates were determined for students in the EGs and CGs. For this analysis, students were deemed “retained” if they were still enrolled or had graduated from the university at the time the transcripts were obtained. Students who had left the university (other than for co-op positions) were considered to be not retained. For this analysis, particular attention was paid to retention rates by gender, since overall success of women was of particular interest. Tables 9 and 10 present the data from this analysis by gender (shading once again signifies random selection).

For the data presented in Tables 9 and 10, the differences in retention rates between the EGs and CGs were significant for women for Study groups 2 ($p < 0.0001$), 3 ($p < 0.0001$), and 4 ($p = 0.051$). Differences for retention rates for women in Study group 1 were similar to those found in the other studies but were not statistically significant, likely due to the small sample sizes. For the male subjects, differences in retention were not significant in any of the four studies.

Table 9. Retention rates for male subjects

	EG1	CG1	EG2	CG2	EG3	CG3	EG4	CG4
Enrolled	13	40	85	200	82	120	12	18
Retained	9	28	64	138	63	84	9	17
Retention rate (%)	69.2	70.0	75.3	69.0	76.8	70.0	75.0	94.4

Table 10. Retention rates for female subjects

	EG1	CG1	EG2	CG2	EG3	CG3	EG4	CG4
Enrolled	11	32	90	161	87	53	11	14
Retained	9	23	80	110	76	38	11	11
Retention rate (%)	81.8	71.9	88.9	68.3	87.4	71.7	100	78.6

Table 11. Engineering retention rates for subjects

	Males		Females		Males		Females	
	EG1	CG1	EG1	CG1	EG2	CG2	EG2	CG2
Enrolled	13	40	11	32	85	200	90	161
Retained in Engineering	9	25	7	17	52	104	69	77
Engineering retention rate (%)	69.2	62.5	63.6	53.1	61.2	52.0	76.7	47.8

For Study groups 1 and 2, the retention rates *within* engineering were also examined (retention rates in Tables 9 and 10 were university retention rates). Table 11 presents data regarding engineering retention rates. Shading signifies random assignment.

For Study 2, the differences in engineering retention rates for women were statistically significant ($p < 0.0002$), but for men, the differences were not significant. This finding is especially important as we strive to improve diversity in engineering.

Summary of Results

In summary, a course designed to improve the 3-D spatial skills of first-year engineering students was developed along with the corresponding materials for instruction. The course was shown to be successful in improving spatial skills as measured by a standardized instrument for both women and men. The course was revised to take advantage of the multimedia software and the workbook that were developed with funding from the NSF in the USA. The multimedia software and the workbook were shown to be successful in improving 3-D spatial skills for first-year engineering students. Through these courses, consistent and large gains were shown through spatial skills training. The gains were similar in random as well as self-selected samples indicating that achievement motivation or other possible underlying variables may not have been significant. In additional studies, the materials were shown to be effective in improving spatial skills for undergraduate students outside of engineering, for students in middle school, and for students in high school.

Sketching has consistently been shown to be a significant factor in spatial skills development, rather than time of exposure, the amount of direct instruction, and the use of the multimedia software. These results were replicated in a controlled study with non-engineering students. However, despite the seemingly low effectiveness of the multimedia software alone as a training medium, undergraduate students appeared to prefer that mode of instruction. Middle school students of similar backgrounds did not show a preference for instruction with the multimedia software indicating that as a student matures s/he may develop a preference for non-traditional instructional methods.

In longitudinal studies, it was shown that students who initially exhibited poor spatial skills and who participated in the spatial skills development course earned higher grades in a number of introductory engineering, mathematics, and science courses at the university when compared to students with weak spatial skills who did not participate in the course. Further, students who participated in the spatial skills training, especially women, were retained at the university at a higher rate when compared to similar students who did not participate in the training.

Conclusions

Engineering educators are quick to recognize student difficulties in mathematics or science and to then develop interventions designed to help these students make the transition to university-level work. Most engineering faculty have highly developed 3-D spatial skills and may not understand that others may be struggling with a topic they find so easy. Furthermore, they may not believe that spatial skills can be improved through practice, falsely believing that this particular skill is one that a person is either "born with" or not. These misconceptions could have a significant negative impact on the success of women engineering students. From the body of work described in this paper, it appears that 3-D spatial skills can indeed be developed through practice. The importance of sketching in developing 3-D spatial skills cannot be understated. By implementing a course aimed at developing the 3-D spatial skills of first-year engineering students, it appears to have had a positive impact on student success, especially for women.

Engineering has many gateway courses. Typically, these are thought to be calculus, chemistry, and physics. From the results of this research, it seems that for women and for some men, engineering graphics may be a more significant gateway than these introductory math and science courses. By developing and implementing a course to help students improve their ability to visualize in three dimensions, we were able to improve student success and retention, particularly for female students.

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