Preparing for Engineering Studies: Improving the 3-D Spatial Skills of K-12 Students

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Abstract – **Well-developed 3-D spatial skills have been shown to be important for success in a number of technological fields including engineering, medicine, chemistry, computer science, mathematics, dentistry, and architecture. Unfortunately, of all the cognitive skills, 3-D spatial skills still exhibit significant gender bias favoring males. Michigan Tech has been offering a remedial course since 1993 aimed at improving the 3-D spatial skills of first-year engineering students, particularly women. In 1998, through funding from the National Science Foundation, multimedia software and a workbook were developed in support of the spatial skills course. In 2003 we received additional funding to test the materials with K-12 audiences. The objectives of the current study are to determine if the materials created for first-year engineering students in our skill-building course are age-appropriate for younger students, and to determine if the materials are effective with these groups in improving 3-D spatial skills, particularly for girls. The materials were tested in a pilot study of middle school students (age ~13) and were recently tested in a high school geometry course (age ~16). Tests designed to assess 3-D spatial skills were given both pre- and post-experience. Students also evaluated each module of the software and workbook to assess ease of use, ease of understanding, and general impressions. This paper will describe the studies conducted with younger audiences and will present initial findings, paying particular attention to gender differences.**

Index Terms – gender differences, K-12 students, multimedia software, and three-dimensional spatial skills

BACKGROUND

Researchers have found that 3-D spatial skills are critical to success in a variety of careers, particularly in engineering and science [1-3]. For engineering, the ability to mentally rotate objects in space has been found to be of particular importance [4]. Unfortunately, of all areas of cognition, 3-D spatial skills still exhibit some of the most robust gender differences favoring males and the most pronounced gender differences are in the area of mental rotations [5-7]. For this reason poorly developed 3-D spatial skills could be a hindrance to the success of women in engineering. At a time when we are actively recruiting women for engineering programs, however, it is important to consider all possible barriers to their success.

In our current educational setting, there is little guarantee that students begin their college studies with well-developed spatial skills. To remedy this, Michigan Tech has been offering a special course aimed at improving the 3-D spatial skills of students who have a demonstrated weakness in that area since 1993 [8]. The original spatial skills course was offered using a "traditional" lecture style with a textbook written specifically for the course.

In 2000, with funding from the National Science Foundation, the Michigan Tech team developed multimedia software and a workbook to replace the original textbook used in the spatial skills course. The software and workbook were thoroughly tested with first-year engineering students and were found to be user-friendly and just as effective in improving spatial skills as was the original textbook [9]. In research conducted in the fall of 2004, the software and workbook were tested with first-year students who were in non-engineering majors. In this study, it was determined that the materials could be used effectively with a non-engineering audience [10]. It was also determined that the software alone was not as effective as when used with the workbook.

In order to demonstrate the appropriateness of the materials for use with a younger audience, research is currently being conducted with high school and middle school students. Initially, it was desired to pilot-test the materials with a younger audience to determine if they would need to be modified for use in a K-12 setting. After completing the pilot study, the materials were used in a high school geometry course as a part of the regular curriculum. The remainder of this paper describes the results from the pilot study conducted in the spring of 2005 and provides initial data for our work with high school students.

PILOT STUDY

The pilot school was a small secondary school in a rural setting. The district has a large population of at-risk and economically disadvantaged students, with 44% of the school's students qualifying for free or reduced lunch. However, the eighth grade state testing scores (MEAP) for the pilot school and for the subset of pilot study students were above the state average in all categories as shown in Table I.

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TABLE I
PERCENT PASSING IN 8TH GRADE MEAP TESTS

Test Component	Pilot Group	Pilot School	State
Math	100%	84%	62%
Science	88%	73%	65%
Social Studies	63%	46%	30%

The eighth grade class at the pilot school consisted of 37 students in total with a wide range of learning abilities. Students are required to take an Integrated Technology course that integrates the use of computers, graphing calculators, scientific probes, Geographic Information Systems (GIS), and Global Positioning Systems (GPS) with their core courses in science, mathematics, social studies, and English. Due to scheduling issues, the students in the pilot study group were honor roll students who were highly motivated, had strong math skills, and were highly organized. Of the 16 students in the pilot study, there were twelve females and four males.

I. Methodology

The spatial skill-building materials were implemented as a part of the Integrated Technology course at Jeffers High School. Typically, the students spent 2-3 days each week working on a module, with the remainder of the course time spent on other topics. One to three class periods, of 54 minutes each, were required for each module.

For each module, the teacher first previewed the module introduction from the workbook with the students, emphasizing the important ideas they would acquire from the computer tutorial, and pointing out any sections where they should pay special attention. The teacher then observed and assisted the students 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. The students were not required to complete all of the workbook exercises, but were required to stay on task and complete as many of the exercises as possible in the time allowed. The teacher continued to observe and assist the students as they worked the exercises.

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 also given a set of snap cubes to use, similar to the blocks used by the Michigan Tech engineering students.

The students were asked to evaluate each module upon completion. The results from these attitudinal surveys are given in Tables II-V. In viewing the data in the tables, it should be noted that the modules were numbered according to the following scheme:

1. Isometric Pictorials
2. Multiview drawings/Orthographic Projection
3. Flat Patterns
4. Rotation of Objects about a Single Axis
5. Reflections and Symmetry
6. Cross-Sections of Solids
7. Surfaces and Solids of Revolution
8. Combining Objects

TABLE II.
RESPONSES TO "HOW WELL DID YOU UNDERSTAND THE EXERCISES THIS WEEK?"

Module	1	2	3	4	5	6	7	8
Very Well	7	2	5	7	5	8	8	11
Well	8	12	10	10	10	9	8	4
Little			2			1		
Not at all		1				1		

TABLE III
RESPONSES TO "WHAT HELPED YOU TO UNDERSTAND THE WORK THIS WEEK?" (MORE THAN ONE RESPONSE PERMITTED)

Module	1	2	3	4	5	6	7	8
Workbook Examples	2	4	3	3	4	5	5	3
Software	7	7	8	14	10	16	14	13
Teacher	7	5	11	7	5	3	3	2
Other Students	8	10	11	10	10	13	13	10
Workbook Exercises	13	7	9	12	9	11	8	9
Blocks	12	13		13	2			
Nothing		1						

TABLE IV
RESPONSES TO "WHICH DO YOU PREFER WORKING WITH?"

Module	1	2	3	4	5	6	7	8
Workbook	5	8	5	1	5	3	1	3
Computer	8	1	3	1	2	2	4	1
Both	10	8	9	14	10	12	11	11

TABLE V
RESPONSES TO "DID YOU HAVE ENOUGH TIME TO LEARN THE MATERIALS THIS WEEK?"

Module	1	2	3	4	5	6	7	8
More than Enough	1	13	2	2	2	4	3	4
Enough	13	4	12	14	10	13	12	10
Needed More			3				2	1

In analyzing the data presented in these tables, some interesting observations can be made. The majority of the students felt that they understood the material (Table II) and that they were given enough time to complete the exercises appropriately (Table V). Most students stated a preference for working with *both* the multimedia software and the workbook (Table IV). This is in contrast to a similar question asked of the non-engineering university students who participated in a 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 [10].

In examining the responses reported in Table III, it is interesting to note that working with other students was routinely selected as a choice for a feature that helped them understand the material. Based on the fact that 12 of the 16 students were female, this finding supports earlier work that indicates a strong preference for collaborative work among females [10]. The workbook exercises and the software received high marks for nearly every module. The blocks were used only for certain modules (1, 2, & 4), and they were rated highly for each of these sessions.

II. GAINS IN SPATIAL SKILLS

In research conducted at Michigan Tech since 1993, the primary instrument used to assess 3-D spatial skills has been the Purdue Spatial Visualization Test: Rotations (PSVT:R) [11]. A sample problem from the PSVT:R is shown in Figure 1. A modified version of the PSVT:R test was used as a pre- and post-test to measure improvements in spatial skills. The modifications made to the original test were: 1) the number of items was reduced from 30 to 14, 2) the number of choices on each item was reduced from five to three, and 3) a time limit was not imposed. The rationale for these changes was to make sure that the test was not overwhelming for the eighth grade students. All of the students completed the modified version of the test within about 10 minutes.

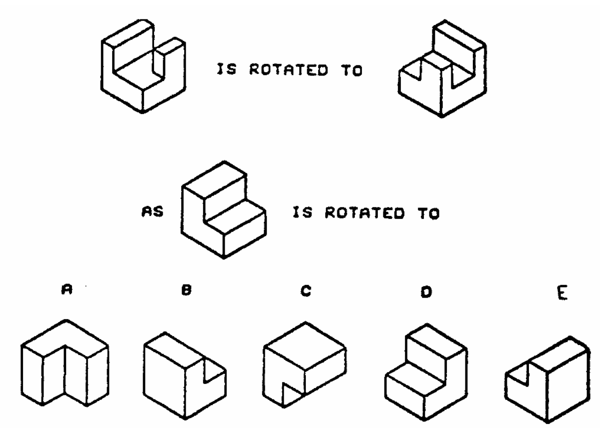

FIGURE 1. PSVT:R SAMPLE PROBLEM

Figure 2 shows the results from the pre- and post-testing. The line y=x indicates no change in the two scores—the students above the line showed an increase in their score, while those below the line showed a decline in their score.

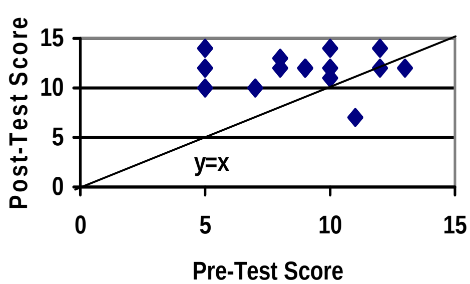

FIGURE 2. SCATTER PLOT OF PRE- AND POST-TEST SCORES

Table VI includes data from the pre- and post-testing with the modified PSVT:R in terms of means, medians, and standard deviations for the students in the pilot study.

TABLE VI.
RESULTS FROM PRE- AND POST-TESTING

	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%

In performing statistical analysis on the data, the average gain was 20.5%. In performing a t-test, the average gain was determined to be statistically significant ($p<0.005$), even though the sample size was relatively small.

TESTING WITH HIGH SCHOOL STUDENTS

In the fall of 2005, the software and workbook were utilized in a high school geometry course as a regular part of the curriculum. Statistically significant gains on the modified PSVT:R were observed for the spring 2005 pilot group students; however, it was noted that the PSVT:R test only measures a person's ability in one component skill of 3-D spatial visualization—rotation of objects. A new test was formulated, drawing on problems from three different 3-D spatial skills tests as well as the modification of items from a fourth spatial skills test. The four types of problems included in this newly devised test were designed to assess four different components of 3-D spatial visualization. Each section of the test consisted of 10 problems, meaning that the new test consisted of 40 problems in total. Ten problems were included from the PSVT:R. Figures 3-5 show examples from the remaining three types of problems included on this test.

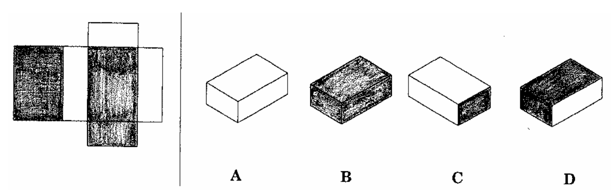

FIGURE 3. SAMPLE FOLDING PROBLEM

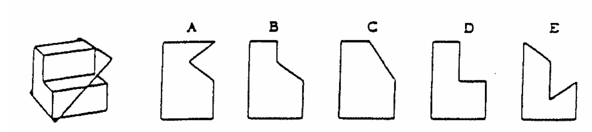

FIGURE 4. SAMPLE CUTTING PROBLEM

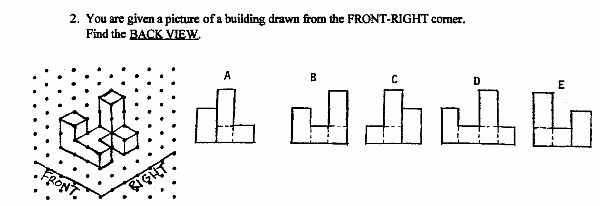

FIGURE 5. SAMPLE ISOMETRIC PROBLEM

Students completed the software and workbook modules as part of their regular coursework in the Geometry class. The spatial visualization unit was taught near the beginning of the academic year so that students would be able to utilize these topics as needed throughout the remainder of the year. Most of the students in the class were in the 10th grade; however, there were a few 9th grade students in the class. Students were also queried at the beginning of the class regarding whether they had participated in shop classes in either high school or middle school. Table VII includes the data regarding shop class participation by gender for this group of students.

TABLE VII
SHOP PARTICIPATION BY GENDER

	Have Not Taken	Have Taken	Currently Taking
Male	7 31.8%	13 59.1%	2 9.1%
Female	13 72.2%	4 22.2%	1 5.6%

Gender differences in shop participation were statistically significant (p=0.0262), with boys more likely to take shop classes than girls.

Other background variables such as playing with computer games, playing with construction toys, and playing with video games were also examined and gender differences were also observed in playing with construction toys and playing with video games. In each case, boys were more likely to have played with these types of toys/games than were girls (p=0.0604 construction toys; p=0.0043 video games).

The new test was administered to 40 students enrolled in high school geometry at Hancock Central High School (22 male; 18 female). Correlations between the four spatial skills components measured by the test were computed to determine if there is an underlying "spatial ability." The correlation matrix for this analysis is shown in Table VIII.

TABLE VIII
CORRELATIONS BETWEEN COMPONENT SPATIAL SKILLS

Test Component	Rotation	Cutting	Folding	Isometric
Rotation	1.000	0.24140 P=0.1061	0.35768 P=0.0838	0.41262 P=0.0044
Cutting	0.24140 p=0.1061	1.000	0.45162 P=0.0016	0.46971 P=0.0010
Folding	0.25768 p=0.0838	0.45163 P=0.0016	1.000	0.34621 P=0.0184
Isometric	0.41262 p=0.0044	0.46971 P=0.0010	0.34621 P=0.0184	1.000

Correlations between component spatial skills scores are generally strong, especially between the "isometric" component and the other three components. These strong correlations could support the notion that there exists an overall "spatial ability" that transcends the individual component skills.

Pre-test scores were also examined for gender differences for each of the component skills. Table IX includes pre-test scores by gender for this analysis.

TABLE IX
PRE-TEST SCORES BY GENDER

Test Component	Rotation	Cutting	Folding	Isometric
Male	61.3%	32.7%	58.6%	45.5%
Female	46.1%	30.0%	71.1%	41.1%

Gender differences were significant for only the Rotation component skill (p=0.0136) for the pre-test. It should be pointed out that there was a significant difference (p=0.0172) on the Isometric portion of the test for students who had participated in shop classes compared to those who had not. Because there were significant gender differences in shop participation, when shop participation was controlled for, the gender differences were not statistically significant on the isometric component. This means that shop participation is more significant in predicting isometric visualization skills than is gender.

At the end of the spatial skills training sessions, students were again administered the modified spatial testing instrument as a post-test. Table X includes the data from the pre- and post-testing.

TABLE X
PRE- AND POST-TEST SCORES BY GENDER

		Rotation	Cutting	Folding	Isometric
Male	Avg Pre-Test	61.3%	32.7%	58.6%	45.5%
	Avg Post-Test	80.4%	43.6%	72.7%	70.5%
	Avg Gain	19.1%	10.9%	14.1%	25.0%
Female	Avg Pre-Test	46.1%	30.0%	71.1%	41.1%
	Avg Post-Test	64.4%	37.2%	80.0%	65.0%
	Avg Gain	18.3%	7.2%	8.9%	23.9%

The data presented in Table X 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. Further testing of these materials with K-12 audiences is underway at this time.

CONCLUSIONS

Multimedia software and a workbook developed for use in a first-year engineering course designed to improve spatial skills were pilot tested with middle school students and were then utilized in a high school geometry course. The K-12 students involved in this study were able to effectively use the materials and spatial skills were improved; however, the gender gap in spatial skill-levels was not narrowed through this intervention. Additional work with K-12 audiences is needed to determine the most effective means for closing this achievement gap.

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