Developing 3D Spatial Skills for K-12 Students

Lisa Rafaelli
Jeffers High School

Sheryl A. Sorby
Michigan Technological University

Kedmon Hungwe
Michigan Technological University

ABSTRACT

Three-dimensional spatial skills have been shown to be critical to success in engineering and other technological fields. Well-developed 3D spatial skills are particularly important for success in engineering graphics courses. Further, 3D spatial skills of women lag significantly behind those of their male counterparts, which could hinder their success in engineering graphics. Michigan Tech has been offering a special course aimed at improving the 3D spatial skills of engineering students, particularly women, since 1993. In a recent study, the materials developed at Michigan Tech were tested with a group of middle school students. This paper will summarize the findings obtained from our outreach to middle school students. Future plans for testing with additional K-12 audiences will be discussed.

INTRODUCTION

Spatial skills in 3D are critical to success in a variety of careers (Barke, 1993; Norman, 1994; Smith, 1964; National Research Council, 2006). There are demands on spatial skill from a broad range of technical tasks such as using Geographic Information Systems (GIS), reading and interpreting, maps, X-rays, and using engineering and architectural drawings (Leopold, Sorby, Gorska, 1996; Black, 2005; National Research Council, 2006). Spatial skills are also important in K-12 education, notably in science and mathematics (National Research Council, 2006). Mathewson (1999), for example, has identified a range of topics in physics that require spatial visualization skills. Among these are nature of shadows, reflections, relative motion, and frame-of-reference orientation. Weak spatial skills have been associated with relatively poor scores on some aspects of mathematics (Casey, Nuttall, & Pezaris, 2001), the impact being relatively greater on female than male students (Tartre, 1990; Sherman, 1980). The importance of teaching spatial skills in the K-12 curriculum has been acknowledged, most explicitly through the National Council of Mathematics standards (NCTM, 2000).

For engineering, the ability to mentally rotate objects in space has been found to be of particular importance (Gimmestad, 1990). Unfortunately, these skills still exhibit some of the most robust gender differences favoring males (Anastasi, 1958; Maccoby & Jacklin, 1974; Sherman, 1978; Levine, Huttenlocher, Taylor, Langrock, 1999). For this reason poorly developed 3D spatial skills could be a hindrance to the success of women in engineering (Leopold, Sorby, Gorska, 1996; Alias, Black & Gray, 2002). In our current educational setting, there is little assurance that students begin their college studies with well-developed spatial skills. At a time when the recruitment and retention of women in the engineering fields is a national priority, it is important to consider removing all possible barriers to their success. To remedy this, Michigan Tech has been offering a special course aimed at improving the 3D spatial skills of students who have a demonstrated weakness in that area since 1993 (Sorby & Baartmans, 1996). 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 the original textbook (Sorby, 2004). In research conducted in the fall of 2004, the software and workbook were tested with first-year students who were in non-engineering majors. It was determined that the materials could be used effectively with a non-engineering audience (Sorby, Drummer, Hungwe & Charlesworth, 2005). It was also determined that the software, when used together with the textbook, was more effective than the software when used alone.

In order to evaluate the appropriateness of the materials for use with a younger audience, research has been conducted with middle and high school students. This paper presents findings obtained from a study with middle school students. The study targeted 8th graders to test the materials in a K-12 setting. Results from two studies, a pilot and follow-up study, are presented.

STUDY 1

Goals of study 1

The purpose of the pilot study was to determine if the materials that were initially developed for first-year engineering majors could be used effectively with 8th grade students as is, if modifications to the materials would be necessary for successful implementation, or if an entirely new approach is required for this audience.

The students were observed as they worked through the materials to determine the how they used the materials, their level of interest in the materials and tasks over time, their levels of understanding, and the efficacy of the instructional strategies that were used. Through these observations, a timeline was established for each module.

Gender differences were not examined as part of the pilot study due to the small sample size. The study could however be used to determine how the participants, who were predominantly female, responded to the course of study, and how well they learned the spatial skills that were taught.

METHODOLOGY

SUBJECTS

The study was conducted at a small secondary school in a rural setting, with a K-12 enrollment of 450 students. The third author implemented the study in her 8th grade classroom. The class had a total of 37 students. However, as a result of scheduling issues, the students were broken into two sections. Sixteen students participated in the study. Fifteen of the participants were honor roll students and were enrolled in the Algebra I course. One participant was a special education student. There were twelve females and four males. Table 1 compares the performance of the students in mathematics and science relative to their cohort group within the same school and across the state. The comparison is based on performance on the statewide Michigan Educational Assessment Program (MEAP). All 16 students had passed the MEAP examination in mathematics, and fourteen (88%) had passed the examination in science.

Table 1: *Percent Passing in 8th Grade MEAP tests*

	Study 1 (pilot)	School	State
Math	100%	84%	62%
Science	88%	73%	65%

MATERIALS

The teacher was provided with workbooks for each of the students. Each of the workbooks was accompanied by software. The software used colorful shapes rendered to appear three dimensional along with interactive animated effects to give students the impression of playing a computer game while honing their visualization skills. The students were also given a set of snap cubes (blocks) to use. Students could use the snap cubes to form and manipulate 3D shapes, as an aid for thinking about and conceptualizing spatial relations.

DESIGN AND PROCEDURE

The pilot study was designed with no control group as a one-group pre-test-post-test study. Spatial visualization was taught as part of an Integrated Technology course during the Spring semester, 2005. The course was designed to integrate the uses of computers, graphing calculators, scientific probes, Geographic Information Systems (GIS), and Global Positioning Systems (GPS) with core courses in science, mathematics and social studies. The course was taught over a period of 9 weeks, one module being completed per week. The following modules were taught, in the given sequence:

1. Isometric Drawings and Coded Plans
2. Orthographic Drawings
3. Flat Patterns
4. Rotation of Objects About a Single Axis
5. Rotation of Objects About Two or More Axes
6. Object Reflections and Symmetry
7. Cutting Planes and Cross-Sections
8. Surfaces and Solids of Revolution
9. Combining Solids

The time spent on each module ranged from 1-3 class periods. The duration of a class period was 54 minutes. The remainder of the course time was spent on other topics. The teacher kept a journal as part of the data collection process. She used it to document her observations on how the students used and responded to the materials.

The students were grouped into pairs for the duration of the study and worked with their partner pairs on the computer and workbook exercises. For each module, the teacher first previewed the module with the class, introducing the relevant sections from the workbook. She introduced the relevant components from the software, pointing out sections they should pay special attention to. The students were not required to complete all of the exercises, but were required to stay on task and work on as many of the exercises as possible in the time allotted. The teacher observed and assisted the students as they worked the exercises.

In view of the fact that the materials had been designed for college students, it was decided to ask students to evaluate each module upon completion, to determine how well they responded to the materials. The students were asked to rate their level of interest in the materials, their level of understanding, and their preferred approaches to the use of the materials. The main questions were:

- How well did you understand the exercises this week? *(4-point scale ranging from 'very well' to 'not at all').*
- What helped you to understand the work this week? *(Six options including 'the work book'; 'the software'; and 'talking to another s tudent.' Students were to check all the option that applied).*
- Which do you prefer working with? *(Re sponse options from: (a) Computer software only; (b) Workbook only; (c) Both computer software and workbook).*
- Did you have enough time to learn the materials? *(Response options from: (a) More time than I needed; (b) Enough time;*and *(c) Not enough time).*

RESULTS

The first set of results focuses on findings from the weekly surveys of students, and the second, on students' learning as determined through a pre- and post-test. The Wilcox Matched-pairs Signed Ranks was used to test the null hypothesis that the difference in pre- and post-test means was not statistically significant. The results from the surveys are presented first.

RESULTS FROM THE SURVEYS

The results from the surveys are given in Tables 2-5. Survey data was collected for all the modules except one (*Rotation of objects about 2 or more axes)*. The teacher's journal has been used to fill in some of the gaps in information. Table 2 summarizes the response to the question, "How well did you understand the exercises this week?" The question was asked in order to track the students' self-rating of their level of understanding for each module.

According to the data, the students believed that they understood the workbook activities. Only one student reported not understanding a module (module 2, *Orthographic drawings*). Two students reported understanding module 3 (*Flat patterns*) "a little."

Students were asked to indicate what helped them to understand the materials. They were to check all the options that were applicable from a given list (Table 3).

The workbook exercises and the software received high ratings for nearly every module. The evidence indicates that the students believed that peer interaction was an important resource for learning for all the modules. The lowest number checking this option was 7 for module 1, peaking for modules 7 (*Cutting planes and cross-sections*) and 8 (*Surfaces and solids of revolution*) at frequencies of 13 and 12 respectively. The findings point to the potential value of peer interaction as an

Table 2: *Responses to "How well did you understand the exercises this week?*

Module	1	2	3	4	6	7	8	9
Very Well	7	2	4	6	5	7	7	11
Well	7	13	10	10	10	9	9	3
Little			2					
Not at all		1						

Table 3: *Responses to "What helped you to understand the work this week?"*
(More than one response permitted)

Module	1	2	3	4	6	7	8	9
Workbook Examples	2	4	3	3	4	6	5	3
Software	6	7	7	13	10	16	13	12
Teacher	7	6	10	7	6	3	3	2
Another Student	7	10	10	9	10	13	12	9
Workbook Exercises	13	8	10	12	10	9	8	9
Snap cubes (Blocks)	12	15		14	2			
Nothing		1						

Table 4: *Responses to "Which do you prefer working with?"*

Module	1	2	3	4	6	7	8	9
Workbook	5	8	5	1	5	3	1	2
Computer	0	1	3	1	2	2	3	1
Both	9	7	8	14	8	11	11	11

Table 5: *Responses to "Did you have enough time to learn the materials this week?"*

Module	1	2	3	4	6	7	8	9
Number of lessons	3	3	2	3	2	1	1	1
More than enough time			2	2	2	3	3	4
Enough time	14	12	11	13	9	13	10	9
Needed more time		4	3	1	4		2	1

instructional strategy. Based on the fact that 12 of the 16 students were female, this finding is consistent with earlier work that indicates a strong preference for collaborative work among college female students (Sorby, Drummer, Hungwe & Charlesworth, 2005). In her report, the teacher implementing the study observed:

The use of partner-pairs allowed me to spend additional time with the students who were having trouble with a concept, as small questions were often answered within the partner-pair. I also believe that working in a team helps make the learning of new material less intimidating and more enjoyable, which may especially benefit female students. The female students in the pilot study enjoyed working as a team.

In addition to the software, students were provided with snap cubes (blocks) for creating and manipulating 3D shapes. The blocks were highly rated for three of the modules: module 1 (Isometric drawings and coded plans); module 2 (Orthographic drawings); and module 4 (Rotation of objects about a single axis). Although no survey was done for the module 5 (Rotation of objects about two or more axes), the teacher's journal indicates that the blocks were used extensively.

The workbook and the computer software covered the same content. Students were asked to indicate their preference between working on the computer only, using the workbook only, and using both the computer software and the workbook (Table 4). A clear majority preferred to work with both. It was also notable that the workbook alone was more highly rated than the computer alone. The maximum number of students choosing the software only option was 3 on modules 3 and 8.

Overall, the data suggests that the use of the materials was optimized by the use of multiple resources and strategies, depending on the module. The use of student pairs was a successful strategy as a learning resource and for building the students' confidence to learn.

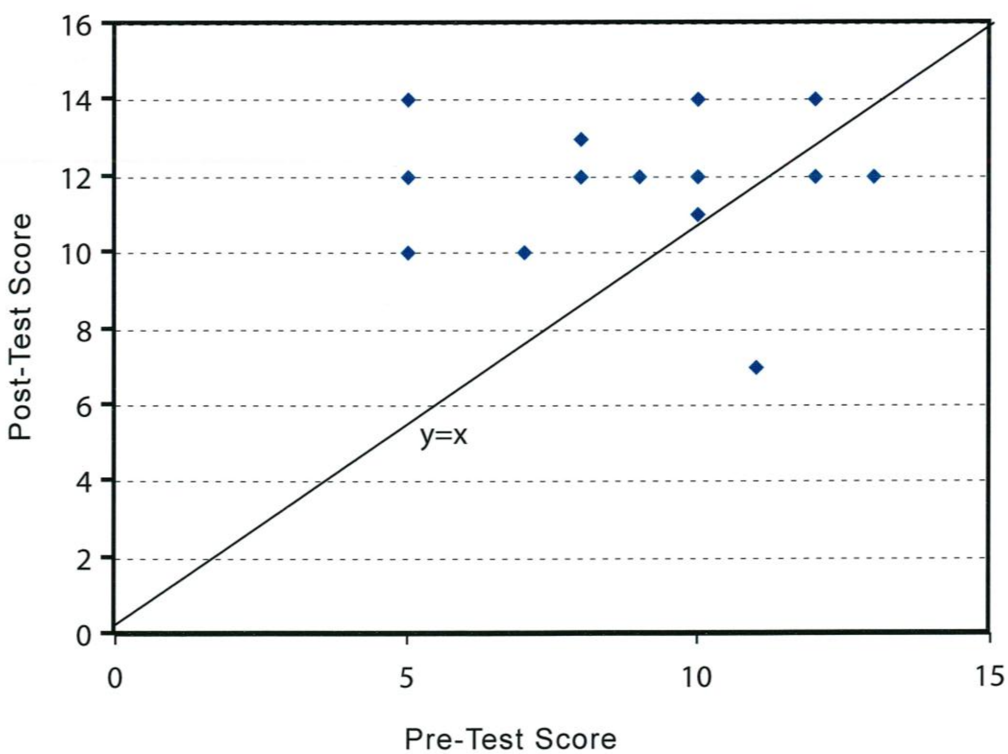
Another goal of the pilot was to establish the optimum time allocation for the activities. One to three class periods, of 54 minutes each were allocated for each module. Table 5 indicates the time allocated for each module. On the whole, the students were satisfied with the time allocations. However, the teacher did report a decline in motivation as the course progressed, and the novelty of the activities wore off. This was also confirmed by self-report data from the students about their levels of interest. The teacher has suggested spreading the activities over a longer time span, for example, a whole semester.

In summary, 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 the response of college students to the same question in a study conducted during the fall semester of 2004. The university students preferred to use the software alone for training purposes, even though it was the least effective mode for developing their 3D spatial skills (Sorby, Drummer, Hungwe & Charlesworth, 2005).

GAINS IN SPATIAL SKILLS

A modified version of Purdue Spatial Visualization Test: Rotations (PSVT: R) test was used as a pre- and post-test to measure improvements in spatial skills (Guay, 1977). The test was modified as follows: 1) the number of items was reduced from 30 to 14; 2) the number of choices on each of the multiple choice items 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. Approximately two weeks after students took the modified post-test, they were given the unmodified 30-item PSVT: R test. Most were done in 20 minutes. All were done in 30 minutes. The mean post-test score on the unmodified version of the PSVT: R was nearly 10% lower than the average score on the modified version of the instrument. The correlation between the test results for the modified and original Purdue Spatial Visualization Test: Rotations (PSVT: R) was moderately strong ($r = 0.604$; $p < 0.01$).

Figure 1: *Scatter Plot of Pre- and Post-test Scores*



The mean values for the pre- and post-test on the modified test were 8.93 (SD=2.52) and 11.87 (SD=1.78) respectively. The maximum attainable score was 14. Figure 1 is a scatter plot of pre- and post-test data. The graph includes the line with y = x (that is, pre-test= post-test), which has been included to enhance interpretation of the data. The students whose pre-test post-test point lies above y = x had had a positive gain in their scores. Points below the line indicate a negative gain. The scatter plot indicates a somewhat mixed picture with some students gaining, others declining, and others remaining marginally the same. There appears to be an overall gain in scores. To test the null hypothesis that the difference in pre- and post-test means was not statistically significant, the Wilcox Matched-pairs Signed Ranks Test was used. It is a non-parametric test that can be used in place of the t-test for correlated groups (Pagano, 2004). The test considers the ranks of the gains in scores and their direction. The decision criteria is: If $T_{obt} \leq T_{crit}$, reject Ho, where T is a sum of the ranks. The analysis yielded $T_{obt} = 11.5$, with $T_{crit} = 15_{one\text{-}tailed}$. The difference between the pre- and post-test was therefore statistically significant, indicating that the learning experience with the course materials was effective in improving spatial skills.

DISCUSSION

The results from the pilot study showed that the materials developed for Michigan Tech's first-year engineering students are suitable for use with a younger audience. The students were confident of their ability to learn from the materials and their capacity to learn was confirmed by significant gains in the post-test scores. The pilot study indicated that students made use of the workbook, the software, and the snap cubes (blocks), the level of use of each component depending on the unit. The findings also highlighted the importance of teacher mediation and the use of peer mentoring in the learning process. The amount of time that the students required to complete the exercises was typically longer than that required by the Michigan Technological University students.

Although the pilot study group was an above-average group of 8th graders, the course instructor, who has more than ten years teaching experience, believes that the materials are age-appropriate for all students of that grade level.

STUDY 2

Goals of Study 2

The pre- and post-test evaluation for Study 1 was based on the Purdue Spatial Visualization Test: Rotations (PSVT:R). The instrument measures skills in *mental rotation* only. However, the course materials (workbook and the software), also covered aspects of spatial skill that were not tested such as *Isometric drawings and coded plans, Cutting planes and cross-sections,* as well as *Folding patterns.* In Study 2, a more comprehensive instrument was used in order to measure learning in the three areas that had not been tested.

METHODOLOGY

PARTICIPANTS

The teacher who conducted Study 1 conducted the second study. There were 8 girls and 16 boys, all enrolled in an 8th grade Integrated Technology class. Twelve of the 24 students were honor roll students and two students had special needs.

Twenty of the students (or 83.3%) had passed MEAP examinations in mathematics, which is the same as the percentage passing for the school as whole. Twenty-one of the students (or 87.5%) had passed the MEAP examination in science. Table 6 summarizes the background data for the group on MEAP in both science and mathematics.

Table 6: *Percent Passing in 8th Grade MEAP tests*

	Study 2	School	State
Math	83.3	84%	62%
Science	87.5	73%	65%

MATERIALS

The instrument used in the second study was made up of items drawn up from the following sources: the Purdue Spatial Visualization Test: Rotations; the Mental Cutting Test (College Entrance Examination Board, 1939); and the Differential Aptitude Test: Space Relations (Bennett, Seashore & Wesman, 1973); and the Middle Grades Mathematics Project Spatial Visualization Test (MGMP, 1981). The authors developed a few additional items covering isometric and orthographic drawings. The total number of items in the test instrument was 40, arranged in four sections: *Mental rotation, Cutting planes, Folding patterns*, and *Isometric drawing*. Each section had 10 questions. All aspects of the test were covered by the workbook and software. Cronbach's alpha was computed to determine the internal consistency (reliability) of the instrument. The analysis was based on a separate sample of eighty 8th grade students who took the test. Alpha was 0.79 indicating an acceptable level of consistency.

DESIGN AND PROCEDURE

The study was designed as a one-group pre-test-post-test study, with no control group. Spatial visualization was taught during the Fall semester, 2005. The course was identical to the pilot course except for the instrument used to test the students.

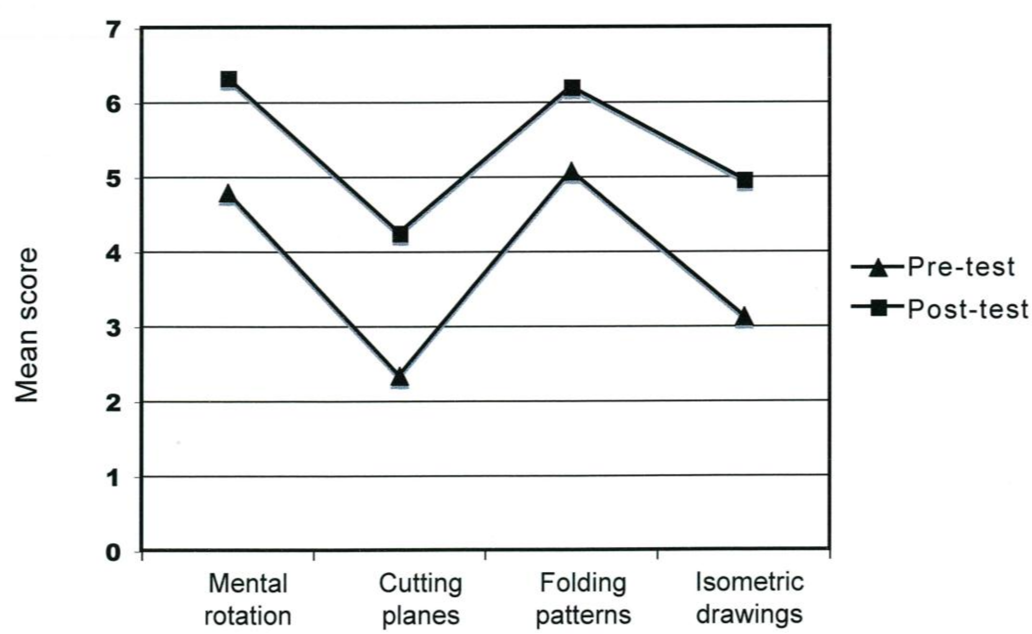
RESULTS

Figure 2 is a graph of the pre- and post-test means of each of the four components of the spatial skills that were tested. The components are: 1) *Mental rotation;* 2) *Cutting planes*; 3) *Folding patterns;* and 4) *Isometric drawings*. There were gains in all four components.

The gains were on average, comparable in magnitude across the four components, indicating responsiveness to instruction. The initial level of skill was relatively lower for the components *cutting planes* and *isometric drawings*. These would appear to be the components that the students had the least experience in prior to participating in the study.

The learning gains for the full test were determined by computing the difference of the pre-test from the post-test for each student.

Figure 2: *Pre- and post-test for four components tested*



The maximum learning gain was 19, minimum gain -1, and mean gain 6.4. Figure 3 indicates the frequency distribution of the learning gains in z-scores (skewness -0.663 and kurtosis 1.04). The skewness and kurtosis values are within the acceptable error limits for a normal distribution (Tabachnick & Fidell, 1996).

The mean values for the pre- and post-test were 15.4 (SD=8.2) and 21.75 (SD=7.4) respectively, on a 40-point scale. A paired samples t-test yielded a statistically significant difference on the tests outcomes ($t=6.635$; $df=23$; $p<0.000_{\text{one-tailed}}$). The learning gains were therefore statistically significant indicating that the materials were effective.

CONCLUSION

The studies indicated that the workbook and software materials developed by Sorby & Wysocki for college students in engineering were effective when used with middle school students. Two key components were added in the schools study: active teacher involvement, and the use of peer mentoring. In the college studies, students worked individually on the materials. The students identified both peer mentoring and teacher guidance as significant sources of their learning.

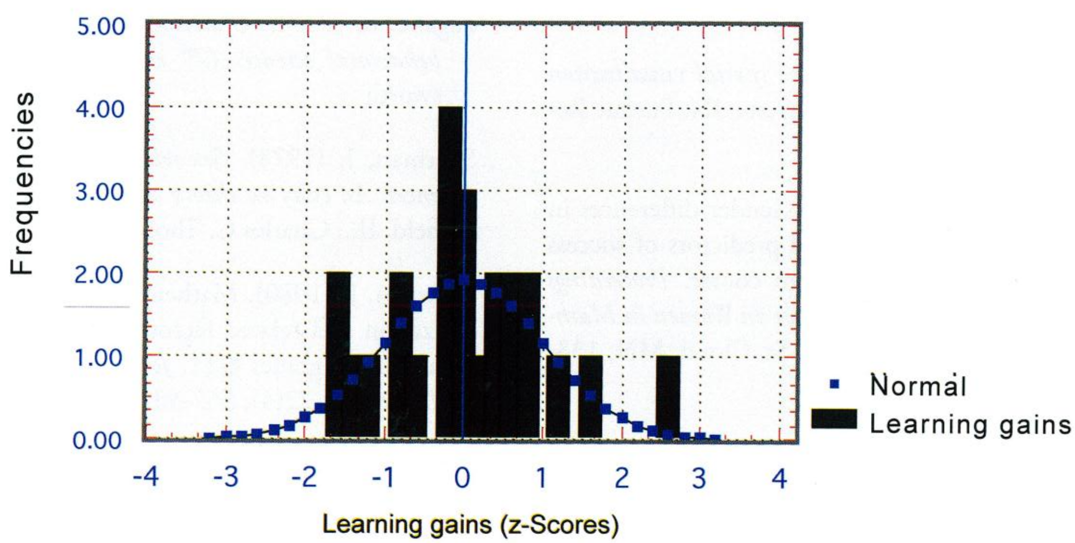
The studies in schools have been expanded to a total of six schools, including both middle school and high school students. We are currently investigating the uses of the materials by teachers of Mathematics, Science, Industrial Technology, and in extra-curriculum programs. The goal is to explore optimum strategies for integrating spatial visualization in the K-12 curriculum using authentic school contexts.

In previous studies with college students, the materials have been proven to be effective in preparing students to learn engineering graphics. Additional studies are underway to investigate the impact of training in spatial visualization on student performance in non-engineering fields (e.g. Chemistry), at college level.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of this project from the National Science Foundation through grant HRD-0429020.

Figure 3: *Standardized histogram of learning gains*



REFERENCES

Alias, M., Black, T.R. & Gray, D.E. (2002). Effect of instructions on spatial visualization ability in civil engineering students. *International Education Journal. 3(1), 1-12.*

Anastasi, A. (1958). *Differential psychology: Individual and group differences in behavior* (3rd ed.). New York: Macmillan.

Barke, H. D. (1993). Chemical education and spatial ability. *Journal of Chemical Engineering, 70*(12), 968-971.

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

Black, A. (2005). Spatial ability and earth science conceptual understanding. *Journal of Geoscience Education*, 53(4), 402-414.

Casey, M.B., Nuttall, R.L. & Pezaris, E. (2001). Spatial-mechanical reasoning skills versus mathematics self-confidence as mediators of gender differences on mathematics subtests using cross-national gender-based items. *Journal for Research in Mathematics Education*, 32, 28–57.

College Entrance Examination Board (1939). *CEEB Special Aptitude Test in Spatial Relations* New York: Author.

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

Gimmestad, B. J. (1990). Gender differences in spatial visualization and predictors of success in an engineering design course. *Proceedings of the National Conference on Women in Mathematics and the Sciences,* St. Cloud, MN, 133-136.

Leopold C., Sorby, S. & Gorska, R. (1996). Gender differences in 3D visualization skills of engineering students. In Andrzej Wyzykowski, et. al. (Eds.) *Proceedings of the 7th International Conference on Engineering Computer Graphics and Descriptive Geometry*, Cracow, Poland 18-22 July 1996, 560-66.

Levine, SC, Huttenlocher, J., Taylor, A., & Langrock, A. (1999). Early sex differences in spatial skill. *Developmental Psychology*, 35, 940–949.

Maccoby, E. G. & Jacklin, C. N. (1974). *The psychology of sex differences.* Stanford, CA: The Stanford University Press.

Mathewson, J. H. (1999). Visual-spatial thinking: An aspect of science overlooked by educators. *Science Education*, 83 (1), 33 – 54.

Middle Grades Mathematics Project (MGMP, 1981). *Spatial visualization test.* Educational Princeton, NJ: Testing Service.

National Council of Teachers of Mathematics (NCTM) (2000). *Principles and standards for school mathematics.* Reston, VA: Author.

National Research Council (2006). *Learning to think spatially.* National Academies Press.

Norman, K.L. (1994). Spatial visualization-A gateway to computer-based technology. *Journal of Special Educational Technology, XII*(3), 195-206.

Pagano, R. (2004). *Understanding statistics in the behavioral sciences (7th ed.).* Thomson/Wadsworth

Sherman, J. (1978). *Sex-related cognitive differences. An essay on theory and evidence.* Springfield, IL.: Charles C. Thomas.

Sherman, J. (1980). Mathematics, spatial visualization and related factors: Changes in girls and boys, grades 8-11. *Journal of Educational Psychology*, 72(4), 467-482.

Smith, I. M. (1964). *Spatial ability-Its educational and social significance.* London: University of London.

Sorby, S. A. & Baartmans, B. J. (1996). A course for the development of 3D spatial visualization skills. *Engineering Design Graphics Journal*, 60(1), 13-20.

Sorby, S. A. (2004). Assessment of a 'New and improved' course for the development of 3D spatial skills. *Proceedings of the 59th Annual mid-year meeting of the Engineering Design Graphics Division of ASEE* (pp. 25-31). Williamsburg, VA: Engineering Design Graphics Division of ASEE.

Sorby, S. A., Drummer, T., Hungwe, K., & Charlesworth, P. (2005). Developing 3D spatial visualization skills for non-engineering students. *Proceedings of the 2005 ASEE Annual Conference*, Portland, Oregon.

Tabachnick, B. G., & Fidell, L. S. (1996). *Using multivariate statistics (3rd ed.).* New York: Harper Collins.

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