# The Development and Assessment of a Course for Enhancing the 3-D Spatial Visualization Skills of First Year Engineering Students

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## ABSTRACT

**In January 1993, we received NSF funding to develop a pre-graphics course for freshman engineering majors who are weak in 3-D spatial visualization skills. A text and computer lab exercises utilizing I-DEAS software were written specifically for this course. The course is 3-credits (quarter system) with two hours of lecture and two hours of computer lab each week. It was offered at Michigan Technological University (MTU) for the first time during the 1993 Fall term and has been offered each fall since that time. The objective of the course is to provide the prerequisite spatial skills needed by students to succeed in their subsequent engineering graphics courses. Assessment for the course has been continuous. Recently, a six-year longitudinal study was conducted to determine the overall success of this project. This paper will describe the project and the assessment findings from the longitudinal study.**

## I. INTRODUCTION

Visualization of problems is critical for success in engineering education. In most cases, it is an essential ingredient for student understanding. It is recognized that the ability to visualize is an important tool required of engineers in order to function effectively.[1–4] In addition to the traditional visualization tasks associated with engineering design, enhanced visualization skills are necessary to function in this new age of Computer Aided Design. In fact, Norman[5] found that a person's spatial ability is the primary factor that explains differences in performance in fully utilizing computer-based technology. Unfortunately, at a time when visualization skills are increasingly important to students, engineering graphics (the primary course where students first learn visualization concepts) has been de-emphasized, and in many cases, dropped from engineering curricula altogether.[6]

*A. The Development of 3-D Spatial Ability*

According to Piagetian theory, an individual acquires spatial visualization ability through three distinct stages of development.[7] In the first stage, children learn topological spatial visualization where they are able to discern an object's topological relationship with other objects—i.e. how close the objects are to one another, an object's location within a group of objects, the object's isolation, etc. In the second stage of development, projective representation is acquired. At this stage, people are able to conceive what an object will look like from different perspectives. In the final stage of spatial visualization development, a person learns to combine projective abilities with the concept of measurement.

There are several standardized tests available to measure a person's ability across the first two stages of spatial development. For example, the Purdue Spatial Visualization Test: Rotations (PSVT:R) was devised to test a person's ability at the second stage of spatial development.[8] A sample problem from the PSVT:R is shown in figure 1. This testing instrument was used throughout this project to identify students who have weaknesses in spatial visualization skills and partially to assess the impact of the experimental course.

The Mental Rotation Test (MRT)[9] is another test designed to assess a person's ability to visualize rotated solids. It consists of 20 items where students are shown a criterion figure on the left and asked to identify which two of four given choices represent the same object after rotation in space. There are 40 points possible on the MRT and a sample problem is shown in figure 2. The Mental Cutting Test (MCT)[10] was first developed as part of a university entrance examination in the USA and consists of 25 items. For each test problem, students are shown a criterion figure that 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 3.

The Differential Aptitude Test: Space Relations (DAT:SR),[11] consists of 50 items. The task is to choose the correct 3-dimensional object from four alternatives that would result from folding the given 2-dimensional pattern. In one study,[12] 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 that were given (including the MCT). A sample problem from the DAT:SR is shown in figure 4.

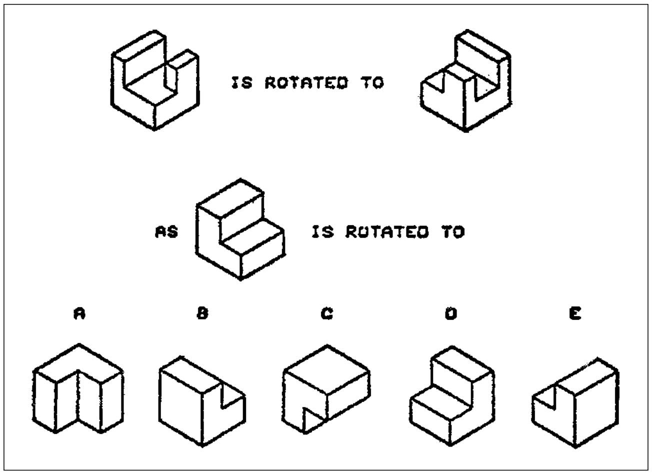


*Figure 1. Sample problem from the PSVT:R.*

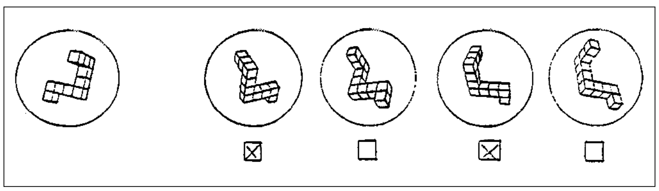

*Figure 2. Sample problem from the MRT.*

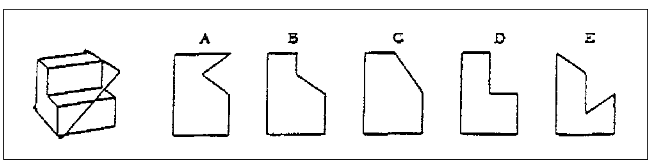


*Figure 3. Sample problem from the MCT.*

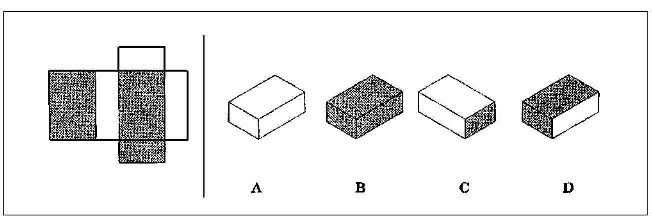


*Figure 4. Sample problem from the DAT:SR.*

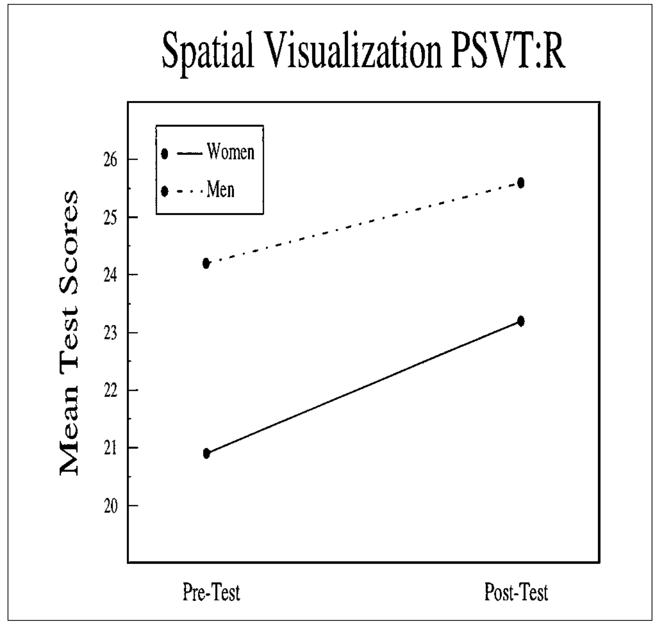


*Figure 5. Pre- and post-test results from engineering graphics course.*

### *B. Background Research at MTU*

It is well-documented that the 3-D visualization skills of women lag behind those of their male counterparts.[3,13–16] Studies conducted at MTU by Gimmestad (now Baartmans) support these findings. A course such as the one described in this paper can help women students address a deficiency in their background so that they are more likely to succeed in their engineering studies (and in particular their design graphics courses). In fact, Hsi et al.[4] found that a Saturday tutorial session on spatial strategy instruction significantly improved the performance of men and women students in an engineering graphics course.

In 1985, Baartmans[17] conducted a research study at MTU. The sample in the study included 365 entering freshman (65 women and 300 men) who had declared Mechanical Engineering as their major. During freshman orientation, the students were given the PSVT:R. A multiple regression analysis established that a student's score on the PSVT:R was the most significant predictor of success in the freshman graphics course (ME105) out of the eleven predictors studied. Two other factors were found significant in predicting student success in ME105: 1) math ACT subtest score, and 2) a combination of prior experience in shop, drafting and solid geometry. Mean scores for women lagged behind mean scores for men on two of the three significant variables—spatial visualization as tested by the PSVT:R and prior years of experience in drafting, shop, and solid geometry. The mean score for women on the spatial visualization test (20.9 out of 30) was significantly lower than that for men (24.2 out of 30). Furthermore, it was expected that students would improve their spatial visualization ability as a result of instruction and other activities in the freshman graphics course. In this study, both genders did improve their performance on the spatial visualization test, however, the mean post-test score for women (23.3) was still significantly lower than that for men (25.6). These results are shown in figure 5.

## II. Project Description

During the Spring and Summer of 1993, we wrote a textbook to be used in our introductory 3-D spatial visualization skills course (GN102, Introduction to Spatial Visualization). This course is viewed as a pre-graphics course at MTU. The course topics include hands on construction activities, paper and pencil activities, and computer activities. These topics and activities are sequenced in logical order for the development of 3-D spatial skills. The topical outline for the ten-week course follows:

Course Outline

Week 1 *Course Introduction.* Students are introduced to the need for visualization skills in fields such as engineering, medicine, architecture, chemistry, and mathematics. The three stages of spatial visualization development are discussed.

Week 2 *Isometric and Orthographic Sketching.* Students are given a set of snap cubes so that they can construct a building according to coded plans. Then they learn how to make isometric and orthographic drawings of the building using grid paper. The use of the snap cubes enables the students to hold a concrete model in their hands as they are making the sketches.

Week 3 *Orthographic Drawings and Applications.* Objects which contain inclined surfaces are demonstrated and orthographic and isometric drawings are made of these objects. Students are also instructed how to set up an engineering drawing in a standard layout.

Week 4 *Pattern Development.* Flat patterns which can be folded into 3-D solids are studied. Students are also introduced to a sheet metal application.

Week 5 *Two- and Three-Coordinate Drawing.* Students are shown the principle involved in locating specific points in space. Then they use a table of coordinate data to draw wireframe geometry. A surveying application using traverse data is introduced.

Week 6 *Translation and Scaling.* Object transformations in 3-space are introduced. Students are required to draw objects after translation and scaling.

Week 7 *Rotation of Objects.* Students work with objects created from snap cubes and sketch isometric views of the objects as they are rotated about one or more axes. These objects are rotated first about one axis and then about two or more axes.

Week 8 *Reflection of Objects and Applications.* Students use Miras™ in class to construct reflected views of objects. The concept of a plane of symmetry for an object is also introduced. Applications from organic chemistry involving reflected molecules are investigated.

Week 9 *Cross-Sections of Solids.* Students are taught to graph planes in 3-space. Cross-sections for cubes, cones and cylinders for cutting-planes of different orientations are discussed.

Week 10 *Surfaces and Solids of Revolution and the Intersection of Solids.* Students are required to sketch the surface/solid which would be formed by revolution of a planar figure/region about an axis. Conversely, given the surface/solid of revolution, they sketch the shape of the planar figure/region which was revolved. The intersection of solids and its use in Computer Aided Design is discussed.

### *A. Computer Lab*

As a part of this project, various computer exercises were initially developed which utilize I-DEAS software as a visualization tool. The exercises were written to adhere closely to those topics covered in the textbook. In January of 1998, we received additional funding from the NSF to develop stand-alone multimedia software and an accompanying workbook to supplement our original textbook. Preliminary assessment results indicate that the multimedia software is likely to be an effective replacement for the original computer exercises as well as for the other course materials originally developed.

## III. Assessment

In 1993, incoming students who were enrolled in the fields of mechanical, civil, environmental, geological, and general engineering were administered the PSVT:R and a background questionnaire as part of their freshman orientation. A total of 535 students took the test, 418 males and 117 females. The average percent correct for male students taking the test was 79.6% compared to an average of 68.1% for the female students. Furthermore, of the 45 students who received perfect scores on the exam, only 3 were women. Thus, 10.0% of the male students received perfect scores compared to only 2.6% of the women students. Conversely, of the 96 students who received scores of 60% or lower, 50 were male and 46 were women. In other words, only 12.0% of the male students failed the exam; whereas, 39.3% of the females failed the exam.

Although women made up only 22% of the group being tested, they were almost 50% of the group failing the exam. Further statistical analyses of the data from the background questionnaire and the PSVT:R test scores revealed four significant predictors of success on the PSVT:R[18] out of eleven factors studied. They were: 1) play as children with construction toys such as Legos™, Lincoln Logs™, Erector Sets™, 2) gender, 3) math ACT scores, and 4) previous experience in design-related courses (like drafting, mechanical drawing, CAD, and art). Furthermore, male/female differences on predictors 1, 3 and 4 were tested for statistical significance. Play with construction toys and previous experience in design courses were found to be gender-biased (i.e., average scores for women on these variables were significantly lower than for men on these two predictors). This means that men were more likely than women to have participated in those activities that were found to be helpful in the development of spatial skills (i.e., play with construction toys and previous drafting course). Average scores on the ACT Math subtest did not differ significantly for men and women. The predictors which were not significant for a person's PSVT:R score were: 1) age, 2) right vs. left handedness, 3) previous experience in high school geometry courses—nearly all of the students had taken high school geometry, 4) participation in industrial arts courses in high school, 5) playing video games, 6) previous work experience involving spatial skills, and 7) participation in sports which involved placing an object in a specific location (e.g., basketball, hockey, etc.)

### *A. Gain Scores on Spatial Tests*

Since its initial offering in the fall of 1993, the course has been taught a total of six times. Each time, the students have been administered the PSVT:R as a part of their final exam (post-test) and their gain scores analyzed. In addition, in the fall of 1996, 1997 and 1998, the students were pre- and post-tested using three other exams also designed to assess their spatial abilities. These exams include the Mental Rotations Test (MRT), the Mental Cutting Test (MCT), and the Differential Aptitude Test: Space Relations (DAT:SR). Gain scores on these exams for the students enrolled in the course have been analyzed, and these results will be presented in this paper.

The PSVT:R has been the primary instrument used both to recruit students for the course and to assess its effectiveness. Figure 6 shows the pre- and post-test results over the past six years for students enrolled in the course. Raw scores are indicated on the figure in parentheses. As illustrated by the data presented in figure 6, the average pre-test score across the six-year period has been approximately 50% compared to an average post-test score of approximately 80%. Dependent t-tests were used to analyze the average gain scores for the students in the class. The cumulative data over the past six years is shown in table 1. (Recall that the number of points possible on the exam is 30.)

Statistically significant gains on the average PSVT:R scores were made by students enrolled in GN102 for each of the six years.

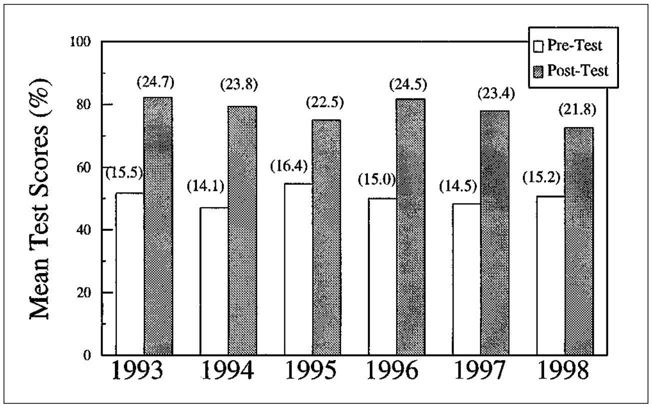


*Figure 6. PSVT:R pre- and post-test results.*

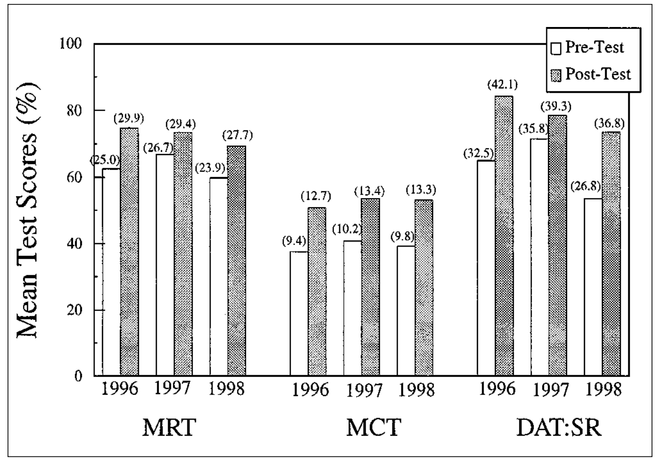


*Figure 7. Pre- and post-test results.*

| Year | Gain (S. Dev.) | t-value | Level of Significance |
|---|---|---|---|
| 1993 (n=24) | 9.17 (3.58) | 12.5 | p<0.0001 |
| 1994 (n=16) | 9.69 (3.62) | 10.7 | p<0.0005 |
| 1995 (n=47) | 6.66 (3.74) | 12.2 | p<0.005 |
| 1996 (n=26) | 9.42 (3.24) | 14.8 | p<0.0005 |
| 1997 (n=27) | 8.89 (4.66) | 9.91 | p<0.0005 |
| 1998 (n=36) | 6.53 (3.75) | 10.46 | p<0.0005 |

*Table 1. PSVT:R average gain scores.*

| Test | Year | Gain (S. Dev.) | t-value | Level of Significance |
|---|---|---|---|---|
| MRT (40 pts) | 1996 (n=26) | 4.85 (5.60) | 4.41 | p<0.005 |
| | 1997 (n=26) | 2.65 (9.23) | 1.47 | 0.05<p<0.1 |
| | 1998 (n=36) | 3.78 (6.12) | 3.71 | p<0.0005 |
| MCT (25 pts) | 1996 (n=26) | 3.27 (3.05) | 5.46 | p<0.005 |
| | 1997 (n=26) | 3.15 (3.64) | 4.42 | p<0.005 |
| | 1998 (n=36) | 3.51 (2.93) | 7.08 | p<0.0005 |
| DAT:SR (50 pts) | 1996 (n=26) | 9.54 (6.91) | 7.04 | p<0.005 |
| | 1997 (n=27) | 3.52 (6.65) | 2.75 | 0.005<p<0.01 |
| | 1998 (n=36) | 9.94 (5.97) | 10.00 | p<0.0005 |

*Table 2. Average gain scores.*

We believe that the post-test gains are due to the positive effects of the course rather than any practice benefit from having used the PSVT:R as both a pre- and as a post-test. Since these tests were administered almost 3 months apart, gains in score due to a practice effect should be negligible. Stanley et al.[19] states that the average gain due to the practice effect for tests administered approximately 3 months apart is usually 0.2$\sigma$ or less. However, the average gain scores for GN102 students were 2.56$\sigma$, 2.68$\sigma$, 1.78$\sigma$, 2.91$\sigma$, 1.91$\sigma$, and 1.74$\sigma$ respectively. Thus, the average gain scores we determined are a factor of ten larger than would be expected from the practice effect alone.

Since the fall of 1996, the MRT, MCT and DAT:SR spatial visualization exams have also been administered to the students in GN102 as both a pre- and a post-test. The MRT has 40 possible points, the MCT has 25 possible points and the DAT:SR has 50 possible points. Figure 7 shows these test results over the past three years (raw scores are indicated in parentheses). Dependent t-tests were also used to analyze the average gain scores for the students in the class. The data for each test and year is presented in table 2. As it can be seen from the data, the GN102 students routinely made statistically significant gains on each test that was administered.

**1) Spatial test reliabilities:** Kuder Richardson-20 (KR-20) test reliabilities were calculated for the pre- and post-tests administered in this study. The KR-20 is a measure of the internal consistency of a test. A KR-20 greater that 0.8 is generally acceptable to most researchers. Table 3 contains the KR-20 data for the tests administered in the Fall of 1997.

As it can be seen from the data presented in this table, the tests that were administered can be deemed "reliable" except for the

| Test | Pre-Test | Post-Test |
|---|---|---|
| PSVT:R | 0.83 | 0.71 |
| MRT | 0.95 | 0.83 |
| MCT | 0.64 | 0.57 |
| DAT:SR | 0.89 | 0.95 |

*Table 3. KR-20 test reliabilities Fall 1997.*

MCT and the PSVT:R post-test. The 1997 PSVT:R post-test reliability is not of concern to us because over the past five years of administering the PSVT:R, the KR-20 has generally been greater than 0.8. As a partial explanation for the low reliabilities on the MCT, it should be noted that the mean scores on both the pre- and the post-test were relatively low (around 50% or lower). Therefore, guessing may have been prevalent due to the difficulty of the test for our students. While the low reliabilities of the MCT with this group of students is of concern, the "noise" introduced by low test reliabilities effectively makes it more difficult for statistically significant gain scores to be attained. Other researchers such as Magin and Churches[20] have reported KR-20 MCT test reliabilities in the 0.86–0.89 range.

*B. Transcript Analysis*

In the Fall of 1993, 96 of the 535 freshman engineering students tested failed the PSVT:R during new student orientation. Of these students, a random sample was selected for participation in GN102. Twenty-four students enrolled in GN102 (experimental group) and the remaining 72 students who initially failed the PSVT:R and did not enroll in GN102 constitute the control group for this study. Since the fall of 1993, virtually all of the students in both the experimental and control groups have graduated and/or left the university. Transcripts of the students in the experimental and control groups have been analyzed regarding their success in engineering graphics courses as well as their overall success in the various engineering curricula. Student transcripts were analyzed to compare performance of the experimental group (EG) and the control group (CG) in several ways: 1) performance in subsequent engineering graphics courses, 2) retention rates and final choice of major, 3) grade point averages, and 4) overall success. During the fall of 1993, the CG consisted of a total of 72 students (40 men and 32 women), and the EG consisted of a total of 24 students (13 men and 11 women). Gender differences were also examined when appropriate. Each of the factors under consideration were examined separately.

**1) Performance in engineering graphics:** Engineering students at MTU enroll in various graphics courses depending on their choice of major. Mechanical engineering students enroll in ME104-Engineering Spatial Analysis and ME105-Graphical Communication in Engineering Design. Civil and environmental engineering students have had changing graphics requirements over the past six years. Initially, civil and environmental engineering students were required to take ME104-Engineering Spatial Analysis and CET-103-Computer Applications. These requirements changed over time resulting in a graphics requirement of GN201-Introduction to Computer Aided Drafting and Design.

ME104 is primarily a course in descriptive geometry; ME105 a course in engineering graphics and conventional practices; CET103 a course in the use of AutoCAD; and GN201 is a solids-based course in computer graphics with components of traditional engineering graphics. Each of the courses is three credits (quarter system) except for CET103 which is only two credits. In addition, there are courses in drafting and computer graphics offered by the School of Technology at MTU taken by some of the students in this study.

Due to changes in major selection or to attrition, not all of the students in this study went on to take a subsequent graphics course; however, 19 of the 24 in the experimental group and 44 of the 72 in the control group took one or more of the graphics courses in subsequent terms. Students sometimes repeated a course if they failed initially or received a D or a D+ in a given course. In these cases, the first grade that they received in a course was used in the analysis. Grade points were assigned to the graphics grades received by the students in the following manner: A = 4, B+ = 3.5, B = 3, C+ = 2.5, and so on. The conglomerate grade point averages for all graphics courses were calculated. The average GPA for the EG was 3.03 (n=29) versus and average of 2.70 (n=73) for the CG. Table 4 details the average GPAs for the two groups by specific course (not including repeats). It is interesting to note that of the students in the CG, no students earned an A in either ME104 or ME105. This was not true of the students in the EG.

On average, students in the experimental group outperformed those in the control group in their subsequent graphics courses. The exception to this was in CET103 which was primarily a training course in the use of AutoCAD—little or no spatial skills were required to perform the tasks in the course. Although there was only one person in the EG who went on to take GN201, the average grade in the course for all students who enroll is typically around a 3.50. Thus, the fact that the average for the CG was 2.77 means that they are performing well below average in that particular course.

Of the 29 first-time graphics grades received by students in the experimental group, only 2 (6.9%) were below a C (i.e., D+, D, or F) compared to 9 out of 73 (12.3%) for the students in the control group. Thus, students in the CG were 50% more likely to do poorly in their subsequent graphics course. Furthermore, for the students in the EG there was only one repeat of a graphics course (5.3%) compared to five repeats for students in the CG (11.4%). Of the ten

| Course | Control | Experimental |
|---|---|---|
| ME104 | 2.23 (n=26) | 2.75 (n=10) |
| ME105 | 2.63 (n=15) | 2.60 (n=5) |
| CET103 | 3.60 (n=15) | 3.33 (n=12) |
| GN201 | 2.77 (n=11) | 3.50 (n=1) |

*Table 4. Average GPA by course.*

total students who received a low grade in their first graphics courses, five eventually dropped out of MTU and three stayed at MTU but left the College of Engineering. Thus, 80% of the students who struggled with their engineering graphics courses were not retained in engineering at MTU.

**2) Retention rates and choice of major:** Retention rates for students in the control group and in the experimental group were analyzed at the end of the Winter 98–99 quarter. Since MTU offers degrees primarily in technical fields, students who drop out typically do so for lack of a non-technical choice of degree (they also drop out for other reasons, but this is true for a large number of those who leave the university). For the CG, twenty-one (29.2%) of the students left MTU compared to six (25.0%) of the students in the EG. Of the twenty-seven students who left MTU, eight (29.6%) left engineering *before* dropping out of the university. Interestingly, the course seems to be having a positive impact on the retention rate of women. Table 5 shows the retention rates by gender for the students in the EG and CG.

Of the students who were retained at the university, retention rates within the College of Engineering were examined. In other words, what percentage of those who persisted at MTU of each group have completed an engineering degree? Of the 51 students in the control group who persisted at MTU, only 42 (82.3%) have remained in engineering majors. For the experimental group, 16 of the 18 (88.9%) who remained are still in engineering. Figure 8 shows the retention rates by gender for the students in this study.

Retention within a curriculum with a strong graphics background was also examined for those students who persisted within the College of Engineering. In other words, what percentage of students ended up in a major where visualization skills are not considered to be critical to student success? (Specifically, these "non-graphically oriented" programs are considered to be chemical and electrical engineering.) None of the students in the experimental group ended up in a non-graphical major compared to eight (19.1%) of the students in the control group. It should be noted that the students in this study were those who had initially enrolled in majors other than chemical or electrical engineering. Thus, it seems that the students in the EG are not discouraged from participation in programs which require well-developed spatial skills.

| Gender | Control | Experimental |
|---|---|---|
| Male | 70.0% | 69.2% |
| Female | 71.9% | 81.8% |

*Table 5. Retention rates by gender.*

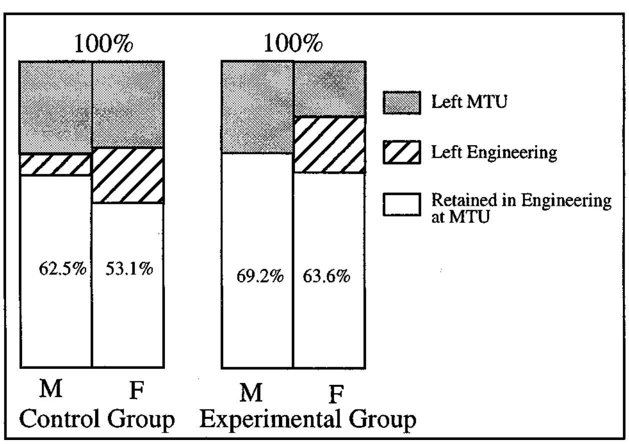


*Figure 8. Retention statistics.*

Overall, 69.2% of the men and 63.6% of the women in the experimental group remained at the university in a graphically oriented engineering program. This compares to 47.5% of the men and 46.9% of the women in the control group. Thus, the students in the EG tend to have better retention rates in every aspect under consideration (overall, within engineering, etc.).

**3) Grade point averages:** Average GPAs were computed for those students who either graduated from the university or who are still pursuing their degrees. There are no differences in overall average GPA between the two groups. The average GPA for the control group is 3.01 and for the experimental group it is 3.00.

Differences in GPA were found within the group of students who dropped out of the university. For those who left the university, the average GPA for the control group was 2.25 compared to 2.47 for the experimental group. However, for the students in the CG, nine of the twenty-one who dropped out (42.9%) had a GPA below a 2.0 compared to only one of six (16.7%) for the EG. Thus, it seems that the students in the CG left for academic reasons whereas the students in the EG may have left for other reasons.

**4) Student success:** Transcripts of the students were examined after the Winter 98–99 quarter. Since the students in the experimental and control groups started in the Fall of 1993, this means that transcripts were examined after an average of approximately 17 quarters of enrollment. Each academic year consists of 3 quarters (most MTU students do not attend summer course offerings). In theory, an MTU degree requires 12 quarters for completion, although it usually takes longer than this in the College of Engineering. The average number of years to completion for engineering students is 4.5 years or 13.4 quarters.

The average number of terms to completion were analyzed for each group. For students in the control group, it took 14.8 terms on average to complete their MTU degree which is identical to the average of 14.8 terms for those in the experimental group. This is interesting in light of the fact that in subsequent years, students who have failed the PSVT:R but who choose not to enroll in GN102 have based their decision on a desire "not to get behind" in the pursuit of their engineering degrees.

## IV. Conclusions

The overall goals of this project were to develop a course which would help "low visualizers" overcome their deficiencies in 3-D spatial visualization and which would help them become more successful in their engineering studies than they would have been without the course. On a variety of spatial tests (the PSVT:R, MRT, MCT, and DAT:SR), students who complete the GN102 course are year after year showing statistically significant gain scores on these tests. Analysis of the transcripts of the students who completed GN102 in 1993 versus transcripts of students in a comparable control group shows the GN102 students having higher graphics grades and higher retention rates in engineering.

## Acknowledgments

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