Developing 3-D Spatial Visualization Skills

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ABSTRACT

The development or improvement of 3-D spatial visualization skills is often cited as one of the major goals of engineering design graphics education. Historically, improvements in spatial skills were achieved as a by-product of a graphics education that often included several semesters of instruction in manual drafting technique. As the engineering curriculum evolved through time, traditional graphics instruction was "squeezed" from two directions simultaneously. First and foremost, engineering programs were required to reduce the total number of credits to graduation, often resulting in fewer credits available for graphics instruction. Second, pressure was exerted on graphics educators to include additional topics such as CAD, design, and creativity in their introductory courses. Instruction in manual drafting technique was greatly reduced or eliminated altogether in favor of sketching and/or computer applications. Throughout this evolutionary process, the objectives of graphics education have changed accordingly. Increased emphasis has been placed on the development of 3-D spatial skills in these courses, however, many graphics educators, who themselves typically have highly developed skills, have had no formal training in understanding spatial skills or how they are effectively developed. This paper will attempt to answer several questions regarding background information on research in spatial skills and will describe those strategies that graphics educators can adopt to develop these skills in their students.

What are Spatial Skills?

In educational psychology research, the distinction is often made between "spatial ability" and "spatial skills." The difference between the two is described briefly in the following. Spatial ability is defined as the innate ability to visualize that a person has before any formal training has occurred, i.e., a person is born with ability. However, spatial skills are learned or are acquired through training. For students at the university level, it is virtually impossible to distinguish between spatial abilities and spatial skills because we have no idea of the training (or lack thereof) in which the students have participated prior to the start of their post-secondary education. For this reason, in this paper, the terms "spatial ability" and "spatial skills" will be used interchangeably.

Spatial skills have been a significant area of research in educational psychology since the 1920s or 30s. However, unlike with other types of skills, there is no real consensus about what is meant by the term "spatial visualization skills." For example, some argue that "spatial visualization is the ability to manipulate an object or pattern in the imagination" (Kahle, 1983), whereas others argue that "spatial visualization [involves] complicated, multi-step manipulations of spatially presented information" Linn & Petersen, 1985). Still others maintain that "spatial visualization is the mental manipulation of spatial information to determine how a given spatial configuration would appear if portions of that configuration were to be rotated, folded, repositioned, or otherwise transformed" (Salthouse et. al.,1990).

In an attempt to resolve some of these issues, some researchers have attempted to categorize spatial skills to account for the fact that there is no one, all-encompassing definition of spatial visualization skills. Maier (1994) proposed that there are five components that make up spatial skills. These are:

- Spatial Perception
- Spatial Visualization
- Mental Rotations
- Spatial Relations, and
- Spatial Orientation

Within these broad categories, however, there is some overlap. For example, there are certain activities that could fit within either the Spatial Relations or the Spatial Orientations categories. Tartre (1990), studied the earlier work of McGee (1979), and proposed a classification scheme for spatial skills based on the mental processes that are expected to be used in performing a given task. He believes that there are two distinct categories of 3-D spatial skills–spatial visualization and spatial orientation. The spatial visualization component involves mentally moving an object while the spatial orientation component involves being able to mentally move your viewpoint while the object remains fixed in space. The spatial visualization component is further subdivided into two categories of Mental Rotation and Mental Transformation. The difference between these two categories is that with Mental Rotation, the entire object is transformed by turning in space, whereas with Mental Transformation, only part of the object is transformed in some way. This classification scheme is illustrated in *Figure 1*.

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 that the mind actually works. In fact, he believes, that "Thinking, then, is mostly visual thinking."

This 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

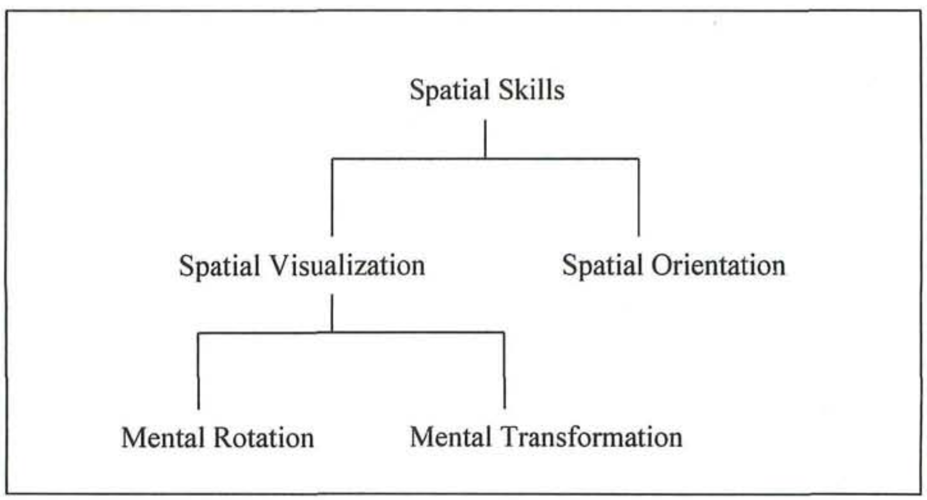

***Figure 1** - Classification of spatial skills.*

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. (p. 54)

McKim (1980), another proponent of the importance of visual thinking, believes that visual thinking is carried on by three kinds of imagery: 1) the kind that we see: "People see images, not things," 2) the kind that we imagine in our mind's eye, as when we dream, and, 3) the kind that we draw, doodle or paint . He also believes that expert visual thinkers utilize all three types of imagery in a flexible, interactive way. He likens this interactive imagery to the diagram shown in *Figure 2*. Where seeing and drawing overlap, "seeing facilitates drawing and drawing invigorates seeing." Where drawing and imagining overlap, "drawing stimulates and expresses imagining and imagining provides the material for drawing." Where imagining and seeing overlap, "imagination directs and filters seeing while seeing provides raw material for imagining." He states that "the three overlapping circles symbolize the idea that visual thinking is experienced to the fullest when seeing, imagining, and drawing merge into active interplay" (McKim,1980).

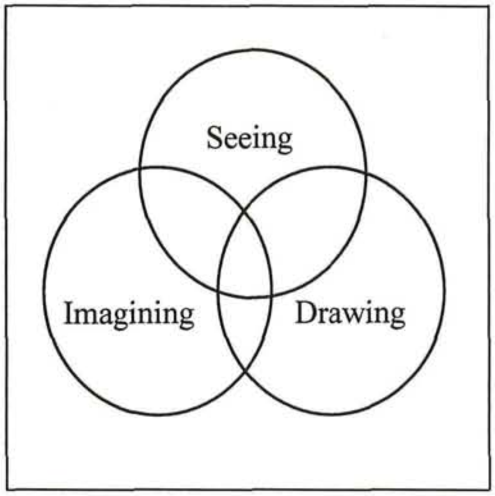

***Figure 2** - McKim's model of visual thinking.*

How are Spatial Skills Developed?

According to Piagetian theory (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 3-5. 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 three-dimensional 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 or if a new feature such as motion is included, 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-dimensional objects is a significant factor in the development of these skills (McKim, 1980; Sorby & Baartmans, 1996; Sorby & Gorska, 1998; Field, 1994; Bowers & Evans, 1990). 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 (Leopold et al., 1996; Medina et al., 1998; Deno, 1995). 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. Activities that have been found to develop 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-dimensional computer games, 4) participating in some types of sports, and 5) having well-developed mathematical skills.

How are Spatial Skills Evaluated?

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

At the second stage of development, there are numerous tests designed to assess a person's projective skill levels. Since these are 3-dimensional tests, a great deal of educational research has been conducted by engineering graphics educators using these instruments.

The Mental Cutting Test (MCT) (CEEB,1939) was first developed for a university entrance exam in the USA and consists of 25 items. For each problem on the exam, students are shown a criterion figure 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 3*.

The Differential Aptitude Test: Space Relations (DAT:SR) (Bennett et al., 1973) 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 (Medina et al., 1998), it was found that a student's score on the DAT:SR was the most significant predictor of success in an engineering graphics course when compared to three other spatial visualization tests given (including the MCT). A sample problem from the DAT:SR is shown in *Figure 4*.

Several tests have been developed to assess a person's skill levels with regards to mental rotations. The Purdue Spatial Visualization Test: Rotations (PSVT:R) was developed by Guay and consists of 30 items (Guay, 1977).

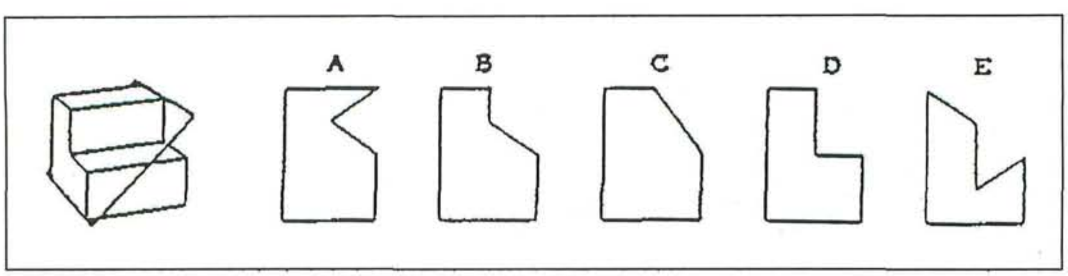

***Figure 3** - Example of the Mental Cutting Test.*

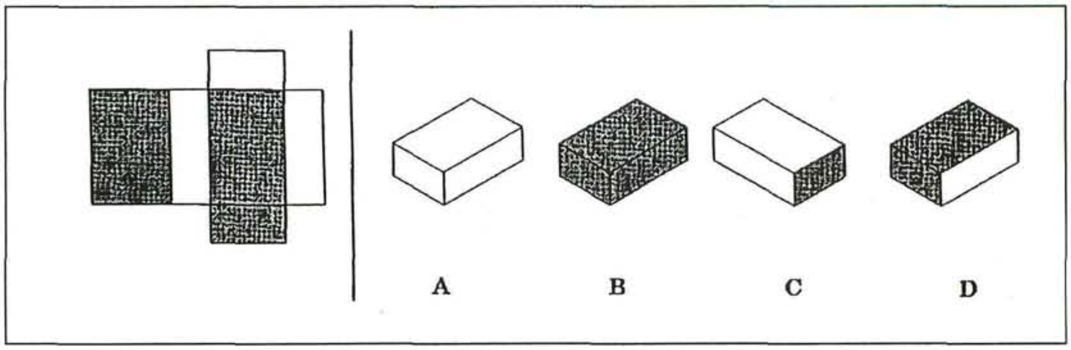

Figure 4 - Example of the Differential Aptitude Test: Space relations.

With this test, students are shown a criterion object and a view of the same object after undergoing a rotation in space. They are then shown a second object and asked to indicate what their view of that object would be if the second object were rotated by the same amount in space. In a previous research study at MTU, a student's score on the PSVT:R was determined to be the most significant predictor of success in an engineering graphics course of eleven variables tested (Gimmestad,1989). In this study, the PSVT:R was the only spatial test given. *Figure 5* shows an example problem from the PSVT:R.

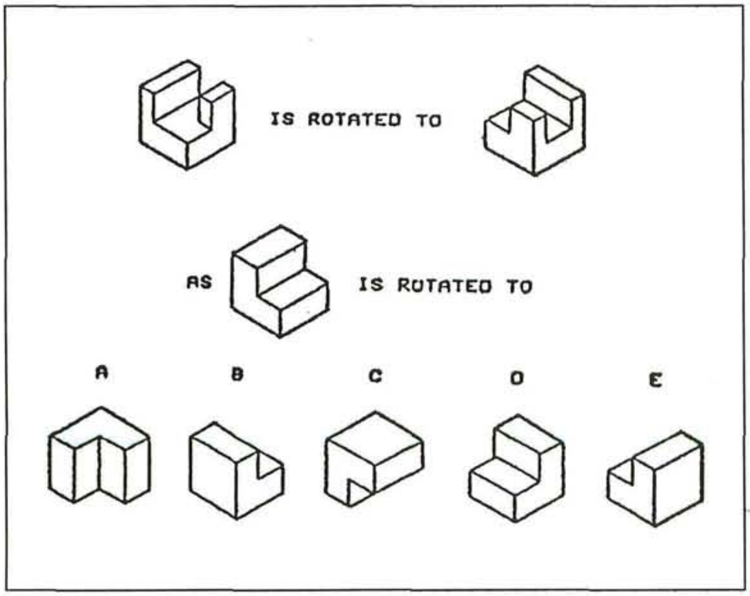

Figure 5 - Example of the Purdue Spatial Visualization Test: Rotations.

The Mental Rotation Test (MRT) (Vandenberg & Kuse, 1978) is another standardized exam used to assess a person's skill in visualizing rotated solids. The MRT was developed by Vandenberg and Kuse and it consists of 20 items. Each problem contains a criterion figure with two correct alternatives and two incorrect alternatives. Students are asked to identify which two of the alternatives are rotated images of the criterion figure. An example problem from the MRT is shown in *Figure 6.*

A third test designed to assess a person's ability to visualize rotated solids is the 3-Dimensional Cube (3DC) test developed by Gittler (1998). This test consists of 18 items, of which only 17 are scored (the first item is a "practice" question). For each question, a criterion figure shows a cube with patterns visible on three sides. Students are told that the criterion cube has different patterns on each of its six sides. The students must choose from six alternatives which one represents a view of the cube that has been rotated in space. Two additional choices, "I don't know the solution" and "None of the cubes is cor-

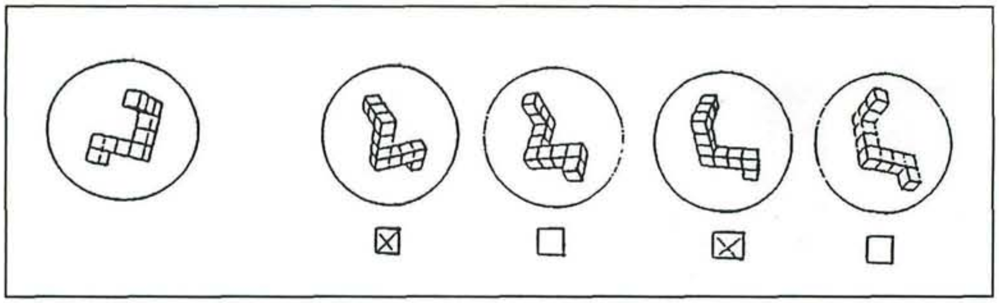

Figure 6 - Example of the Mental Rotation Test.

rect," are also available. This test is not a time-limited test because this could lead to a confounding of speed and power with the measurement of spatial skill levels (it usually takes between 15 and 40 minutes for students to complete the test). An example problem from the 3DC test is shown in *Figure 7.*

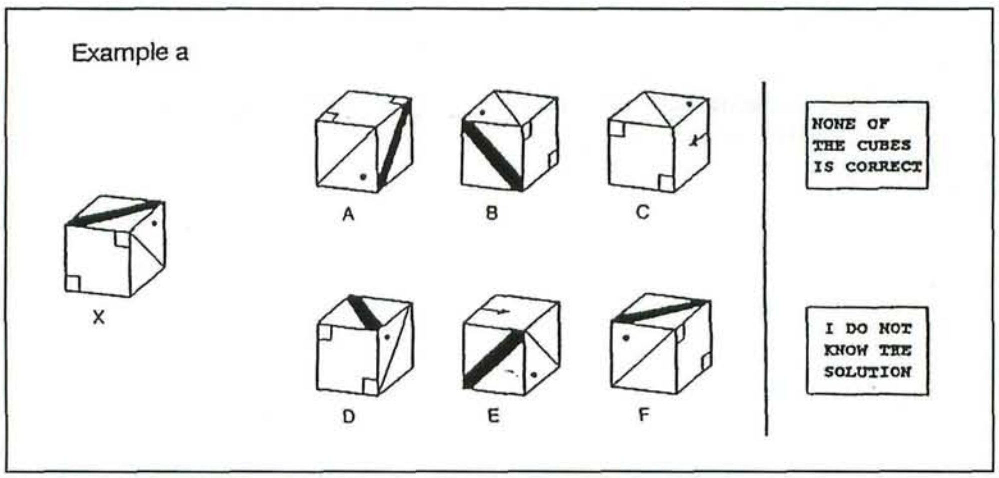

Figure 7 - Example of the 3-Dimensional Cube Test.

Why are Spatial Skills Important for Engineering Students?

Several educational research studies have been conducted in spatial visualization over the years. In 1964, Smith (1964) conducted research in spatial visualization and concluded that there are 84 different careers for which spatial skills play an important role. Maier (1994) concluded that for technical professions, such as engineering, spatial visualization skills and mental rotation abilities are especially important. In research conducted by Norman (1994), it was found that a person's spatial skill level was the most significant predictor of success in their ability to interact with and take advantage of the computer interface. Barke (1993) also found that well developed spatial skills are essential for understanding basic chemistry and structural chemistry. Pleck, et. al., (1990) concluded that due to advances in computer technologies, the importance of visualization skills is rapidly increasing at the same time that graphics is being de-emphasized in the engineering curricula as illustrated graphically in *Figure 8.*

McKim (1980) points out that the ability to think visually is essential not only for artists but also for those in scientific and technical

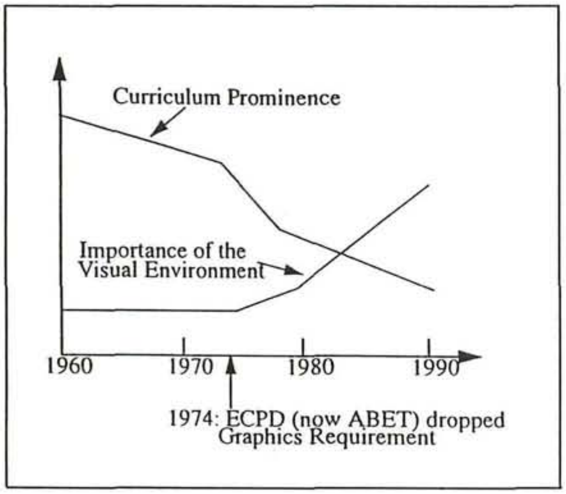

***Figure 8** - Decline in graphics curriculum prominence versus the increasing importance of the visual environment (from Pleck, et al., 28).*

careers. He documents several instances throughout the history of discovery and/or development of technological advances that have had a long-term impact on society as a whole that were made through seeing or visualizing (e.g., the discovery of penicillin by Fleming, the discovery of the helical structure of DNA by Watson, the discovery of the structure of the benzene ring by Kekule, and the development of devices such as the fluorescent light and the A-C generator by Tesla). He further points out that Einstein maintained that his whole mechanism of thought was through visual imagery and that for him (Einstein) it was difficult to put his thoughts into words in a "secondary stage."

In the 1950s a sweeping reform of engineering education was advocated by the now famous Grinter Report (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 nearly a half-century ago, its comments regarding engineering graphics education still ring true today.

Ferguson points out that the very first engineers started as artists during the Renaissance (1992). 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.

Are There Gender Differences in Spatial Skills?

It is well-documented that the spatial visualization skills of women lag far behind those of their male counterparts. Theories for the cause of these differences include the assertion that spatial ability is transmitted as a recessive characteristic on the X-chromosome (Stafford, 1972), that spatial ability is related to a male sex hormone (Heir & Crowley, Jr., 1982), or that environmental factors are the primary reasons for male-female differences in spatial skill levels (Fennema & Sherman, 1977). Studies conducted at MTU (Sorby & Baartmans, 1996; Gimmestad, 1989) and in Poland, Germany and Brazil (Leopold et al., 1996; Medina et al., 1998) indicate that these gender differences are persistent and that they cross international boundaries. In pre- and post-testing (before and after participation in an engineering graphics or descriptive geometry course) using various testing instruments it has been determined that, although men and women both have statistically significant gain scores through participation in these courses, the average post-test scores for women are lower than the average pre-test scores for men. This has been observed for virtually all testing instruments at each university collaborating in these studies. An example of typical results from these studies is shown in *Figure 9*. In this figure, the average scores on the MCT for men and women were computed both before and after participation in an engineering graphics course at MTU during the 1997-98 academic year (Sorby & Gorska, 1998).

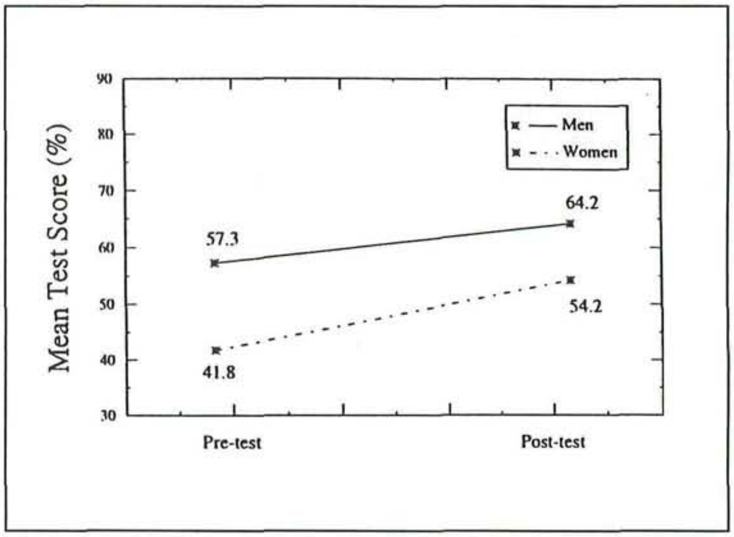

***Figure 9** - Mean test scores for mental Cutting test: Men versus women.*

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 education. 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). This course has been highly successful at MTU since its inception in 1993, however, most engineering programs in the country are reluctant to adopt a similar course due to resource/time constraints.

What can Graphics Educators Do to Enhance Spatial Skills?

In some studies, computer models designed to enhance spatial skills have been shown to assist in the development of visualization skills. Many engineering graphics educators believe that through working with solid models on a computer screen that students will further develop their visualization skills. However, in research conducted at MTU, it was shown that the mere act of working with 3-D computer models in a solid modeling environment do not develop these skills as well as traditional visualization skill-building techniques like sketching (Sorby & Gorska, 1998).

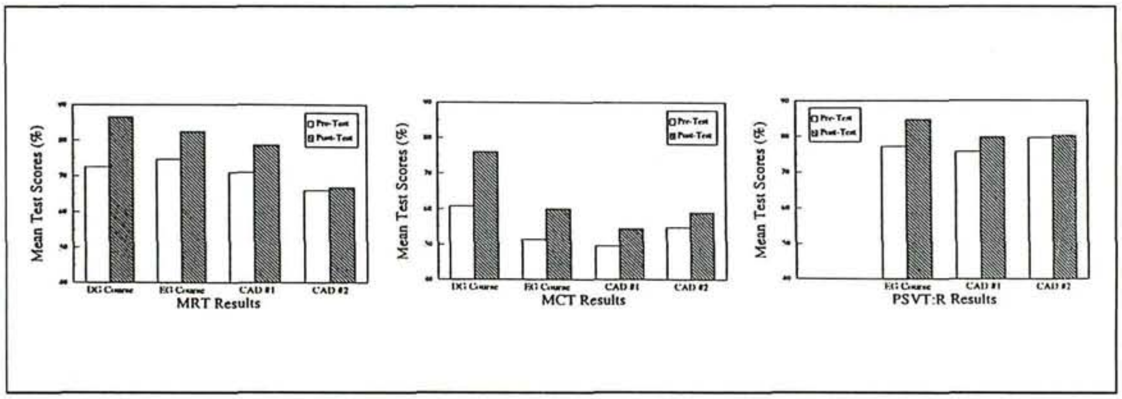

***Figure 10** - Results of pre- and post-testing of visualization skills at MTU.*

In this study, students in various courses at MTU were administered spatial testing instruments as both pre- and post-tests. Two of the courses were essentially computer aided design courses with an almost exclusive emphasis on 3-D modeling using I-DEAS software. In the remaining two courses sketching and/or hand drawing was the primary emphasis of the course work. One course focused on engineering graphics the other course consisted of work in both descriptive geometry and engineering graphics. It should be noted that in the engineering graphics course, many students with previous drafting experience were able to receive placement credit for the course, thus lowering the mean test scores. *Figure 10* shows the results of the pre- and post-testing in these courses. For the data presented in this figure, the gain scores on each test for students in the engineering graphics and descriptive geometry courses were higher for all tests than were the gain scores for either of the two CAD courses. In fact, for the course labeled CAD #2 in this figure, gain scores on the MRT and the PSVT:R were not statistically significant and were only marginally significant for the MCT.

Thus, it seems that in order to develop 3-D spatial skills, the answer is sketching, sketching, sketching! Having the students sketch (or draw) hand-held models seems to be especially helpful in the development of spatial skills. Sketching and drawing are also advocated by McKim (1980), Arnheim (1986), and Ferguson (1992) as a means for developing a capacity for visual imagery and creativity. In our quest to "modernize" the engineering graphics curriculum, if spatial visualization skills are truly a course objective, we should not necessarily eliminate all sketching in favor of 3-D computer modeling.

Providing students with concrete, hand-held models is also helpful in the development of spatial skills. Models that they can both touch and see will stimulate the "perceiving" portion of their brain more than models that they just see on the computer screen (McKim, 1980). Models for showing sectional views are especially helpful in illustrating things like cross-hatched regions vs. non-cross-hatched regions.

Besides providing sketching opportunities and hand-held models, graphics educators should re-think their course outlines in order to better develop spatial skills. In most cases, multi-view sketching is the first or one of the first topics for engineering graphics courses. Most graphics texts are also organized with multi-view sketching/drawing at the beginning. After students have successfully completed numerous missing line and missing view problems, they move on to pictorial sketching. In fact, this sequencing of topics is the opposite of how most educational psychologists say that individuals learn. By learning multi-view sketching first followed by pictorial sketching, we are starting with a topic that is very abstract (multi-view sketching) and following it with a topic that is semi-concrete (pictorial sketching). The dilemma is that without a knowledge of multi-view sketches, we have difficulty in describing objects to our students from which they can construct a pictorial sketch. One answer is to have students work with models when constructing pictorial views. In this way, students can move from the concrete (physical models) to the semi-concrete (pictorial sketching) in the order in which new topics are most readily learned. These models can then be used in creating multi-view sketches at a later time in the course so that students move from concrete to abstract in a natural progression.

A relatively new topic that could be included in conjunction with an engineering graphics course that will likely assist in the development of 3-D spatial skills is mechanical dissection. With mechanical dissection activities, students can be required to sketch assembly drawings of the systems that they are disassembling and then to trade drawings and parts with another team for re- assembly. In this way, students will again be progressing from the concrete to the semi-concrete and by trading with another group will come to realize the importance of good graphical skills in the communication of design information.

Graphics educators can also institute a special course or help sessions for those students who have especially weak spatial skills. This has been implemented at MTU over the past six years with a high degree of success (Sorby & Baartmans, 1996). By identifying and helping those students who have weak visualization skills, engineering graphics educators can institute more challenging problems in their "regular" courses. Students who have weak skills who have participated in special courses or help sessions will likely be less discouraged by their graphics courses and retention may improve. This is especially important for the retention of women engineering students. In a five-year longitudinal study of the visualization course at MTU, it was found that the retention rate within the College of Engineering for women who participated in the initial offering of the course was 63.6% compared to a retention rate of 53.1% for women who failed the PSVT:R but did not enroll in the course (Sorby & Baartmans, 1996). Retention rates within the College of Engineering for male students were 69.2% for those who participated in the course and 62.5% for similar students who did not enroll in the course.

Conclusions

Although there is disagreement about exactly what constitutes spatial visualization skills, it is generally recognized that these skills are important for success in engineering. There are many testing instruments available for assessing spatial skill levels and numerous studies have consistently shown that women students lag significantly behind their male counterparts in spatial abilities. Keys to enhancing spatial skills include sketching, the use of hand-held models, and the reorganization of graphics topics sequencing. Special courses and/or help sessions for students with weak spatial abilities have also been shown to be effective in the development of spatial skills.

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