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International Experiences in Developing the Spatial Visualization Abilities of Engineering Students

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Abstract. Engineers communicate with one another largely by graphical means. For this reason, it is very important that the spatial visualization abilities of engineering students be well-developed. Unfortunately, there is little guarantee that our students come to the university with well-developed spatial abilities. In this paper we will compare the spatial visualization skill-levels for entering engineering students from our universities by means of several tests (Mental Rotations Test, Mental Cutting Test, and Differential Aptitude Test: Space Relations) and evaluate our experiences in improving the spatial abilities of both male and female engineering students. Through international comparisons of our experiences in teaching introductory courses, we will describe the teaching methods that seem to be especially helpful in the development of spatial visualization skills for engineering students.

Key Words: spatial visualization, graphics education, gender differences
MSC 2000: 51N05

1. Introduction

In recent years, there have been reports regarding several different international research studies concerned with aspects in evaluating and improving spatial visualization abilities. The

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interest in this research topic stems largely from the belief that spatial visualization abilities are important to success in scientific and technical fields and that, until this time, the spatial abilities of some individuals were not sufficiently well developed for effective visual communication. In our daily lives, graphical communication is becoming increasingly important through the emergence of computer graphics and multimedia applications. Spatial visualization abilities are especially important for those individuals who are developing and designing the three-dimensional "virtual" environment and for those working in the field of engineering.

In this paper, we will analyze and compare the content and teaching methods employed in our descriptive geometry and/or graphics courses and will determine the significanceof these factors for the development of spatial visualization skills. We will compare the results obtained at three universities: University of Kaiserslautern (UKL) in Germany, Cracow University of Technology (CUT) in Poland, and Michigan Technological University (MTU) in the USA.

We will first compare spatial ability levels by means of several standardized tests for engineering students entering our universities. The testing instruments include:

- the Mental Rotations Test (MRT) [1],
- the Mental Cutting Test (MCT) [2], and
- the Differential Aptitude Test: Space Relations (DAT:SR) [3].

We will compare the test results between students from Architecture, City and Environmental Planning, and Civil Engineering at UKL, Civil Engineering at CUT, and Civil and Environmental Engineering at MTU. The percentages of women in the groups being tested were 43.2% at UKL, 34.2% at CUT, and 28.8% at MTU. Because previous research conducted by the authors determined significant gender differences in spatial visualization abilities (Górska et. al. [4]), in this paper we will examine results by gender as appropriate, especially since we have different proportions of women between our groups.

The use of several testing instruments as well as the determination of correlation levels between student test scores ensures that we are looking at overall spatial abilities and not just the ability to perform a specific spatial task as measured by one test. It should be noted that Saito et. al. [5] found that it is likely that the MCT not only measures spatial abilities but also measures analytical thinking. In this paper we will not attempt to distinguish between these two factors.

At the end of our respective courses, we again tested our students with post-tests accompanied by a post-course questionnaire. The questionnaire asked students to self-assess their course attendance, their level of engagement with homework assignments, and their usual mode employed in completing assignments (i.e., working alone or in a group). By comparing results from the pre- and post-tests with the answers obtained on the post-course questionnaire, we will evaluate differences in course content and teaching style with respect to their effect on the development on spatial visualization abilities. Correlation factors between the pre-tests and the final exam scores for our students will also show if the spatial tests are predictors of success in our respective courses.

2. Introductory courses

At the UKL, students enrolled in architecture, civil engineering, and city and environmental planning are required to enroll in a course in descriptive geometry during their first semester (15 weeks). The number of contact hours (one contact hour = 45 minutes) for the course in which they enroll depends on their declared major: Architecture students enroll in two hours of lecture and two hours of lab per week, and students in Civil Engineering and in City and Environmental Planning enroll in one hour of lecture and one hour of lab per week. (Laboratory hours are defined as "problem solving" sessions, typically in smaller groups, i.e., *Übungen*). In addition, they are required to enroll in various other graphics or drawing courses depending on their major.

In this research we focused on the role of descriptive geometry courses at UKL during the first semester only. The content of the descriptive geometry courses differs slightly by major, but in general, topics include: spatial visualization and visual communication, projection methods, axonometries, multiviews with intersection and measurement assignments, shadow constructions, solids and surfaces and their intersections, and coted projection with applications. Architecture and City and Environmental Planning students are together during the lecture hours (approximately 200 people) and during lab hours, they are divided into three groups of approximately 50–80 students each. For the semester under consideration in this research study, there were only about 25 Civil Engineering students per course (lecture and lab hours combined).

During the lab hours, students work on assignments either alone or in a collaborative group with the instructor circulating as needed to assist the students. In addition, the students get 3–5 homework assignments per semester where they must apply principles from the course material to a given problem. Student attendance during lecture and lab sessions varies between 50% and 90% due to the "non-course" system prevalent at German universities. The students manually draw the example problems and solutions using instruments and spatial visualization is enhanced by the use of hand-held models and by computerized VRML models for visualization of the specific problems. The lectures also include instructions in solving the problems using CAD packages. For their homework assignments, students may choose to work manually or by using a CAD package, however, most of the students solve their problems manually. For the final exam in the course, students are required to complete assignments by manual drawing (1 hour).

At CUT, civil engineering students are required to take a course in descriptive geometry during their first semester. The course consists of 30 lecture hours and 15 lab hours over a 15-week semester (one contact hour = 45 minutes). The lectures consist of approximately 120 students with labs of about 40 students. The topics covered during the descriptive geometry course include: a general overview of projection methods, the Mongean projection method with complicated problems of solid-solid or solid-plane intersections, the theory of 2nd degree surfaces and their intersections, oblique and normal axonometric projection, coted projection with an application in road design, and perspective projection.

Because the time devoted for practice in the classroom is limited to just one 45-minute session per week, a large portion of preparatory work must be done by each student outside of class either individually or in a group. During each lecture session, a specific theoretical topic is delivered in order to explain the background of certain classes of problems and simple tasks are solved as example problems. After the lecture, problems are assigned that students must solve before attending the lab session. During the lab, each student is required to complete an assignment and to turn it in before leaving for the day. Instrument drawing is the typical method employed in solving problems. Students typically turn in about 10 drawings and have two "mid-term" exams during the semester. The final exam consists of two parts: drawing (2.5 hours) and an oral exam.

At MTU, civil and environmental engineering students are required to enroll in two separate graphics courses, usually in their first year, but not necessarily so. The first course that students typically take is GN131-Introduction to Engineering Graphics. (The second course, Introduction to Computer Aided Design, was not a part of this study.) The topics covered in GN131 include: pictorial sketching, object transformations (translation, dilation, rotation, and reflection), multiview sketching, conventional practice, sectional views, and dimensioning practice. The GN131 students also spend 2-3 weeks of class time working with "real-life" engineering drawings where they are given a set of plans obtained from industry and a series of questions related to the graphical information on the plans. In GN131, students spend 4 hours per week in two lab sessions over a 10 week term.

"Mini-lectures" are delivered by the instructors during the first 20–30 minutes of each lab session. Students then work in collaborative groups during the remainder of the session to complete exercises designed to reinforce class materials and to prepare them for the completion of their homework assignments. Class sizes are relatively small (around 30) and the instructor circulates among the groups during the latter portion of the lab session, answering questions and reinforcing topics as needed from the mini-lecture. It should be noted that in this course, due to the interactive nature and the small size, the attendance is typically around 90% or higher for each session. Sketching is the normal mode of graphical communication in GN131 and students are required to keep a Sketch Journal where they spend 15–20 minutes per day sketching three-dimensional objects of their choosing. Drawing with instruments is not covered in the course.

We note some similarities and differences between the courses at each of the universities:

- At each university, the students who were tested typically work during lab sessions in groups of about 30–40 people. However, most of the students at the UKL and at the CUT have lectures in larger groups (50–200).
- The pedagogic method employed at each university during practice sessions involves guiding and supporting students as they solve problems individually or in a team.
- The methods employed for solving problems varies between the three universities: at CUT and UKL a more "traditional" approach is utilized — descriptive geometry topics with the use of instruments to solve spatial tasks, while at MTU sketching predominates.
- The courses at UKL and CUT stress descriptive geometry concepts whereas this type of problem is included in only an extremely limited basis within the graphics course at MTU (the graphics course at MTU stresses practical engineering graphics problems, while students at UKL and CUT complete this type of practical graphics exercises in different courses during their first year).
- At CUT and UKL, spatial visualization abilities are enhanced by solving complicated geometrical problems, with the problems selected from real-life applications. Each theoretical problem typically has its reference in an architectural design project.
- Spatial visualization has been enhanced by employing VRML models at the UKL and by the use of real-life, hand-held models at all three universities.

3. Comparisons of spatial abilities levels

At the beginning of the semester, several tests designed to ascertain spatial visualization abilities were administered to the students in our classes. It should be noted that the students were primarily first-year students who had just begun their university studies. Table 1 includes

University	MCT (Std. Dev.)	MRT (Std. Dev.)	DAT:SR (Std. Dev.)
UKL	63.75 (20.38) $n = 220$	63.27 (21.83) $n = 220$	82.37 (13.32) $n = 220$
CUT	59.80 (19.25) $n = 198$	61.42 (22.17) $n = 196$	82.43 13.77 $n = 160$
MTU	57.56 (18.56) $n = 57$	61.28 (19.40) $n = 55$	81.32 (16.10) $n = 59$

Table 1: Mean pre-test scores and std. dev. in percent correct for entire population

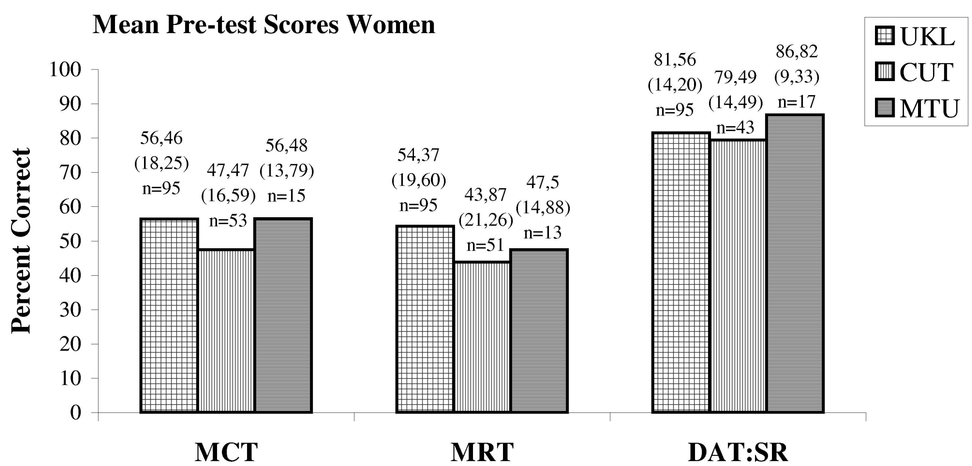

Figure 1: Mean pre-test scores for women at all universities

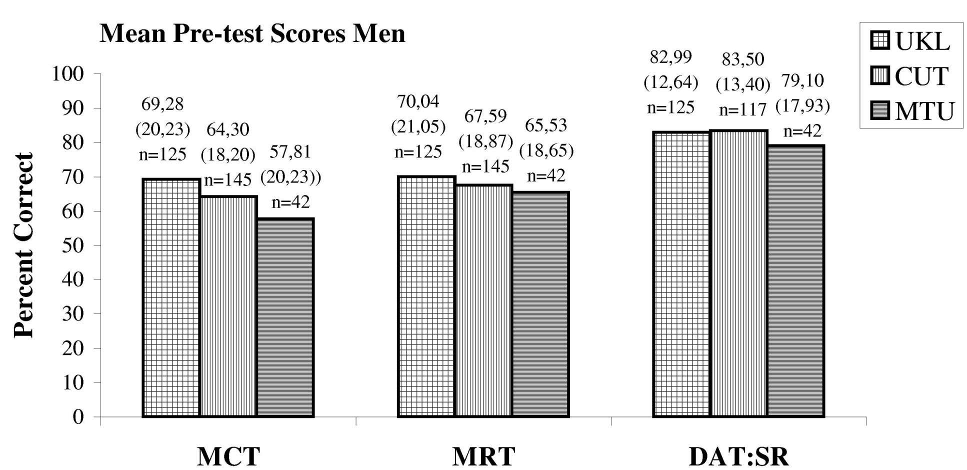

Figure 2: Mean pre-test scores for men at all universities

the pre-test results obtained on the MCT, MRT and DAT:SR for the entire population of students that we tested at our universities. Figures 1 and 2 show the mean pre-test scores by gender for each university. In most cases, significant gender differences were obtained for mean test scores.

At UKL there were significant gender differences on the MRT and MCT ($p < 0.0001$), but not on the DAT:SR. Similar results were obtained at CUT (no significant gender difference on the DAT:SR but significant gender differences on the MRT and the MCT ($p < 0.0001$). At MTU there were no significant gender differences between mean scores on the MCT; there was a significant gender difference on the MRT ($0.001 < p < 0.005$) favoring the males and on the DAT:SR ($0.025 < p < 0.05$) favoring the females. In each case, testing conditions were held virtually identical among the different universities with the exception being that 4.5 minutes were allotted for each part of the MRT at CUT compared to 4 minutes per part at both UKL and MTU.

The data presented in Table 1 was collected during the Fall 1999 semester at both UKL and CUT, during the 1998-99 winter term for the MCT and the DAT:SR at MTU, and during the 1999-00 winter term for the MRT.

3.1. Analysis of differences in mean scores

Using a t-test to compare the mean test scores between the countries, some interesting observations can be made. The results are summarized in Table 2 (X denotes no significant differences in mean test scores) in groups of men (**m**) and women (**w**) separately.

Tests		UKL/CUT	MTU/CUT	UKL/MTU
MCT	**w**	$0.025 < p < 0.050$	$0.025 < p < 0.050$	X
	m	$0.010 < p < 0.025$	$0.010 < p < 0.025$	$0.0005 < p < 0.0010$
MRT	**w**	$0.001 < p < 0.005$	X	X
	m	X	X	X
DAT:SR	**w**	X	$0.025 < p < 0.050$	$0.05 < p < 0.10$
	m	X	$0.025 < p < 0.050$	$0.05 < p < 0.10$

Table 2: Significance of differences in mean pre-test scores

3.2. Correlation between various test scores

Correlation analyses were performed between student scores on the three spatial tests at each of the universities. Table 3 presents the correlation factors obtained from this analysis.

As it can be seen from the data presented in Table 3, there is a high degree of correlation between student scores on each of the three spatial tests administered. Thus, it seems that if students have poorly developed spatial skills, they have difficulty in performing a variety of spatial tasks.

3.3. Final exam scores and spatial pre-tests

Correlation analyses were also performed on pre-test scores and the student scores on the final examinations in each of our respective courses to determine if the spatial instruments were indicators of probable success in engineering graphics or descriptive geometry courses. The final exams for the courses at the three universities differ from each other according the

Tests	UKL $n = 220$	CUT $n = 160$	MTU $n = 57$
MRT/MCT	$r = 0.3818$ $p = 0.000$	$r = 0.5614$ $p = 0.000$	$r = 0.47464$ $p = 0.0002$
MRT/DAT:SR	$r = 0.4206$ $p = 0.000$	$r = 0.5425$ $p = 0.000$	$r = 0.47819$ $p = 0.0002$
MCT/DAT:SR	$r = 0.4228$ $p = 0.000$	$r = 0.5558$ $p = 0.000$	$r = 0.59406$ $p = 0.0001$

Table 3: Correlation between pre-tests

respective course content as described previously. The data from this analysis is presented in Table 4.

University	MCT	MRT	DAT:SR
UKL	$r = 0.4464$ $p = 0.000$	$r = 0.2366$ $p = 0.004$	$r = 0.2055$ $p = 0.014$
CUT	$r = 0.2864$ $p = 0.0002$	$r = 0.3627$ $p = 0.0000$	$r = 0.2424$ $p = 0.0066$
MTU	$r = 0.43963$ $p = 0.0016$	$r = -0.15463$ $p = 0.2888$	$r = 0.23915$ $p = 0.091$

Table 4: Correlation between course final exam scores and spatial visualization pre-test scores

These results show that the MCT pre-test score was a significant predictor of final examination score at each of the three universities. In addition, the MRT pre-test score was a significant predictor of success at both UKL and CUT but not at MTU. A student's score on the DAT:SR was significant (or marginally significant) at each university, however, the significance of this test score was not as high.

4. Development of spatial abilities

At the conclusion of the semester/term, students were again administered the MCT and the MRT as post-tests and the mean gain scores were analyzed for statistical significance. Table 5 includes the data from the pre- and post-testing at our respective universities. (It should be noted that the number of cases is not the same as for the data presented in Table 1 because these results were presented if and only if both tests were taken by a given subject.) The gain scores on each of these tests as analyzed by a dependent t-test, were statistically significant at each university ($p < 0.0001$). At UKL there was also a control group of students from Mechanical and Economic Engineering ($n = 66$) who had only a course in technical drawing with very little descriptive geometry. At CUT, there was a control group of students with computer graphics only ($n = 27$). Students in the control groups had lower gains on both tests (UKL: MCT Gain = 5.88, MRT Gain = 8.22, CUT: MCT Gain = 7.85, MRT Gain = 15.0) when compared to the students in the experimental groups (shown in Table 5). For the MRT the difference in mean gain scores between the control group and the experimental group were statistically significant at both the UKL ($p = 0.001$) and at CUT ($p < 0.005$). Differences

University		MCT PRE-TEST (Std.Dev)	MCT POST-TEST (Std.Dev)	MCT GAIN (Std.Dev)	MRT PRE-TEST (Std.Dev)	MRT POST-TEST (Std.Dev)	MRT GAIN (Std.Dev)
UKL	**w**	57.36 (18.82)	65.36 (16.85)	8.00 (14.01) ($n = 47$)	50.36 (18.20)	73.80 (18.06)	23.44 (20.67) ($n = 48$)
	m	67.44 (20.95)	76.56 (16.22)	9.12 (17.08) ($n = 57$)	69.19 (20.68)	84.07 (16.88)	14.88 (22.38) ($n = 62$)
CUT	**w**	48.68 (16.67)	67.74 (18.30)	19.06 (18.54) ($n = 47$)	44.82 (22.81)	74.21 (21.47)	29.39 (21.00) ($n = 41$)
	m	63.60 (17.90)	76.15 (12.79)	12.55 (16.54) ($n = 130$)	67.71 (18.95)	91.60 (11.14)	23.89 (15.69) ($n = 133$)
MTU	**w**	57.30 (14.30)	69.30 (20.63)	12.0 (11.09) ($n = 12$)	47.50 (15.48)	73.65 (12.65)	26.15 (12.93) ($n = 13$)
	m	59.65 (16.52)	68.94 (16.68)	9.29 (11.09) ($n = 34$)	65.38 (18.28)	81.54 (16.56)	16.15 (15.17) ($n = 38$)

Table 5: Average pre-/post-test and gain scores in percent correct

in mean gains between the control and experimental groups were also statistically significant ($0.025 < p < 0.05$) on the MCT at CUT.

4.1. Analysis of differences in mean gain scores

Mean gains between the universities were compared to determine if different instructional methods and/or course topics affected gain scores between the universities participating in the study. In this analysis, t-tests were performed to determine the significance of differences in mean gains. The results are summarized in Table 6 below (X denotes no significant differences in mean gain scores) in groups of men (**m**) and women (**w**) separately.

Tests		UKL/CUT	MTU/CUT	UKL/MTU
MCT	**w**	$0.0005 < p < 0.001$	X	X
	m	$0.05 < p < 0.1$	X	X
MRT	**w**	$0.05 < p < 0.1$	X	X
	m	$0.0005 < p < 0.001$	$0.001 < p < 0.005$	X

Table 6: Significance of differences in mean gain scores

- There was no statistically significant difference between the mean gains for the women at MTU as compared to either the women at UKL or those at CUT. (This could, in part, be due to the relatively small sample size of women at MTU who were tested.)
- The mean gains for women at CUT were significantly higher than those of the women

at UKL on the MCT ($0.0005 < p < 0.001$), and were marginally higher on the MRT ($0.05 < p < 0.1$).

- There was no statistically significant difference between the mean gain scores for the men at MTU compared to the men at UKL on the MCT or the MRT.
- There was no statistically significant difference between the mean gain scores for the men at MTU compared to the men at CUT on the MCT. The men at CUT had higher mean gains than their counterparts at MTU on the MRT, and the difference was statistically significant ($0.001 < p < 0.005$).
- Mean gains for the men at CUT were higher than those for the men at UKL on both testing instruments and the difference in gains on the MRT was statistically significant ($0.0005 < p < 0.001$) while the difference in MCT gains was marginally significant ($0.05 < p < 0.1$).

5. Post-course questionnaire

By means of a post-course questionnaire, we also examined the relationship between a student's course attendance and commitment to completing the homework and his/her performance on the final exam for the course as well as his/her gains on the spatial tests. The questionnaire consisted of four basic questions:

1) How often have you attended class? (Always, Almost Always, Seldom, or Almost Never)
2) How would you characterize your level of commitment to completing the required homework assignments? (High, Medium, or Low)
3) On average, what was the amount of time you spent completing each homework assignment? (__ hours)
4) For the most part, how did you work on your assignments for this class? a) alone, b) in a group

5.1. Questionnaire responses and final exam scores

At UKL, students responses to questions 1–3 were not statistically significant predictors of success for scores on the final exam, probably because there was not a great deal of variability in the data (i.e., because of the non-course system in Germany, we were not able to administer the questionnaire to students with low attendance and commitment rates). Therefore, at UKL the mean scores on the final exam for the students who filled out the questionnaire were compared to those who did not by means of a t-test (the assumption being that if students were not present to fill out the questionnaire, that they had lower attendance and commitment than those who were present to fill out the questionnaire). Those students who completed the post-course questionnaires did have a significantly higher score on the final exam than those who did not ($p = 0.001$). Therefore, the inference may be drawn that those who rarely or never attended lectures had significantly lower scores on the final exam. Responses to question 4 were statistically significant ($p = 0.0467$), with those who worked in groups scoring lower on the final exam than those who did not. This is probably due to the fact that women were more likely to work in groups than men (Pearson significance of gender bias $p = 0.03301$), and the mean of the final exams scores for women were lower than those of men. Responses to question 4 were analyzed separately for men and for women and no statistically significant difference was found for either the men or the women.

At CUT, students responses to questions 1 and 4 showed statistical significance when compared to final exam scores for the group as a whole ($p = 0.035$ for question 1, $p = 0.0121$ for question 4) and for the group of men only ($p = 0.0022$ for question 1, $p = 0.012$ for question 4). The mean of the final exam score in each case was lower for those who attended lectures and classes "Almost Always" when compared to those who attended "Always". At CUT, it was also found that students who did their work individually outperformed those who worked in a group. Responses to questions 2 and 3 did not yield statistically significant results for success on the final exam.

At MTU, students responses on questions 1, 3, and 4 were not statistically significant predictors for student success on the final examination, however, question 2 did yield statistically significant results. In this case, students who responded that they had a high level of commitment to completing homework assignments outperformed students who reported a medium level of commitment by a significant amount ($p = 0.0093$).

5.2. Questionnaire responses and mean gain scores

At UKL, an ANOVA analysis was performed to determine if there were connections between responses on the post-course questionnaire and the gains on the spatial tests. At UKL it was determined that those men who responded "Always" to question 1 had significantly higher gains on the MRT than those who did not ($p = 0.0319$). Women who characterized their level of commitment in completing their homework projects as "High", had significantly higher gains on the MRT than those who did not ($p = 0.0300$).

An ANOVA analysis performed at CUT of responses on the post-course questionnaire in comparison to gains on spatial exams showed that attendance frequency and personal commitment to homework were not significant predictors of gains scores for either the MRT or the MCT when analyzed separately for men and women. However, high class attendance and individual work (questions 1 and 4) were statistically significant factors for gains on the spatial tests for the group as a whole ($p = 0.0000$ for both tests) when compared to the gains of those who did not self-report high attendance or who worked in groups.

Through an ANOVA analysis performed at MTU, responses to none of the questions on the questionnaire were significant predictors of gain scores on any of the testing instruments.

6. Conclusions

Students enter each of our three universities with differing levels of spatial abilities as measured by various testing instruments. In most cases, the pre-test scores on the spatial tests for students at UKL were higher than those at CUT and MTU as measured in each group as a whole and by gender (although the percentage of women at UKL was the highest among the three universities). Mean pre-test scores for women at CUT were lower than those of their counterparts at both MTU and UKL (differences were not statistically significant for the MRT with MTU nor for the DAT:SR at UKL). The fact that MTU reported no significant gender differences in mean scores on the MCT and significant differences on the DAT:SR favoring the women could be attributed to either a) improvements in spatial skills for women, narrowing the gender "gap", or b) an anomaly for this particular group of students only (recall that the sample sizes for MTU were fairly small). Further research needs to be conducted to determine which of these is more likely.

In this study, both introductory Descriptive Geometry and Graphics courses had a positive impact on improvements in spatial abilities as seen in the highly significant gains between pre- and post-tests on all tests at all universities. Differences in gains between the students at MTU and CUT were generally not significant for either men or for women (the exception being between the men on the MRT), nor were the differences in gains between the students at MTU and UKL statistically significant on each test for either men or women. This is interesting in light of the fact that the students at MTU were post-tested after only ten weeks of instruction (40 lab hours) compared to 15 weeks of instruction at both CUT (30 lecture hours and 15 lab hours) and UKL (15/30 lecture hours and 15/30 lab hours). Differences in mean gains for both the men and women at CUT were higher than their counterparts at UKL for both the MCT and the MRT, with the differences being statistically significant or marginally so. Thus, it seems that the two universities where the course section sizes were smaller (MTU and CUT) resulted in higher gains on spatial tests when compared to a university (UKL) with larger course section sizes. The analysis of the mean gain scores for the women provides evidence that the similar teaching methods and the content of the descriptive geometry courses at UKL and CUT improve visualization skills as measured by the MRT at the same level in both countries, despite the fact that the spatial skill levels on the pre-test were relatively low for women at CUT. The analysis of the gain scores for the spatial tests at MTU, where there is a great deal of "hands-on" problem solving and sketching, illustrates the role of sketching and drawing in the development of spatial abilities. This finding also supports the conclusions stated by Sorby and Górska [6] where it was theorized that courses that stress hands-on sketching and drawing tend to improve spatial skills more than courses that stress Computer Aided Design methods.

As students self-reported on the post-course questionnaires, those who had a high frequency of class attendance had significantly higher gains on the MRT at both UKL and CUT, and significantly higher gains on the MCT at CUT. Women with a high personal commitment to completing homework had significantly higher gains on the MRT at UKL. Responses to post-course questionnaires were not a significant predictor of gains on spatial tests for students at MTU, probably due to a lack of variability in the data (attendance and time spent on homework were generally consistent for the students in the course).

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