



Spatial Visualization Skills Intervention for First Year Engineering Students: Everyone's a Winner!

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Introduction

The connection between spatial visualization skills and performance in engineering coursework is becoming more evident¹⁻³. Spatial visualization skills are typically divided into two principal categories⁴. The first is outward-looking and large scale in that it relates to an understanding of the relative location of the individual to the surroundings and to the relative placement of objects and other individuals in the surroundings. The second category involves the ability to manipulate objects mentally, whether through moving, folding, cutting, or rotating the objects⁵. It is this second category of spatial visualization skills and how it relates to success of engineering students that is of interest in this paper.

There are a number of tests that are applied in the analysis of spatial visualization skills. These include the Differential Aptitude Test: Spatial Relation (DAT: SR), the Mental Cutting Test (MCT), the Mental Rotations Test (MRT), the Revised Minnesota Paper Form Board Test, and the Purdue Spatial Visualizations Test: Rotations (PSVT:R)⁶⁻¹⁰. In studying the capacity of engineering students for performing spatial visualization, the PSVT:R is often preferred, with one rationale being that it includes objects of complex geometries (curved surfaces, etc.) rather than simple structures including only cubes^{11,12}. The ENGAGE Engineering project has made spatial visualization skills, as assessed by the PSVT:R, a principal focus of their efforts to enhance retention and diversity of engineering students, based on considerable work done previously at Michigan Technological University (MTU)^{1,2}. The ENGAGE project provides a curriculum and course materials for teaching spatial skills, also based on the foundational work done at MTU.

The commonly applied PSVT:R requires the student to study the rotation of an object from one orientation to another and then duplicate the rotation on a second object (Figure 1). The rotations increase in difficulty from rotation about a single axis, then about two axes, finally about all three axes. The 30-question test is limited to 20 minutes. Scoring for the test is typically: 0-17 - fail, 18-20 - marginal pass, and 21-30 - pass³. These ranges arise from data suggesting that students scoring below 18 (below 60%) on the assessment benefit significantly from the curricular intervention and that students scoring 18 to 20 (60 - 67%) who receive the intervention outperform their counterparts who do not receive the intervention³.

The application of the PSVT:R to the assessment of engineering students has provided insight into the ways that spatial visualization skills influence success in engineering coursework. As might be expected, students with stronger spatial visualization skills tend to perform more strongly in courses in engineering graphics¹³. Other evidence points to a correlation between spatial skills and success in design courses^{14,15}. It has also been suggested that spatial skill level may serve as a barrier to entering engineering majors, with those students who have not yet developed the skill being unable to persist long enough in engineering curricula to develop the necessary aptitude required to succeed⁵.

On average, underrepresented students and women perform more poorly on spatial skills assessments. The literature on gender, testing, and achievement gaps has been studied from a number of different viewpoints. It continues to be a controversial subject, with some citing significant differences in male/female performance on standardized tests¹⁶⁻¹⁹. However, there are also a number of cases where the gap cannot be attributed just to gender, but perhaps might be more a function of other factors, including socio-economic status (SES), geographical location, and previous association with subject matter^{2, 20}. Gaps are generally found in math, with women performing lower than men in both standardized tests and more conventional classroom assessments²¹. These gaps begin long before students get to college and have seriously impacted the gender balance in engineering disciplines. Recognizing that spatial skills training can improve math performance², assessment and training in spatial skills can serve as a significant lever for increasing the diversity of engineering student populations and, concomitantly, the engineering workforce.

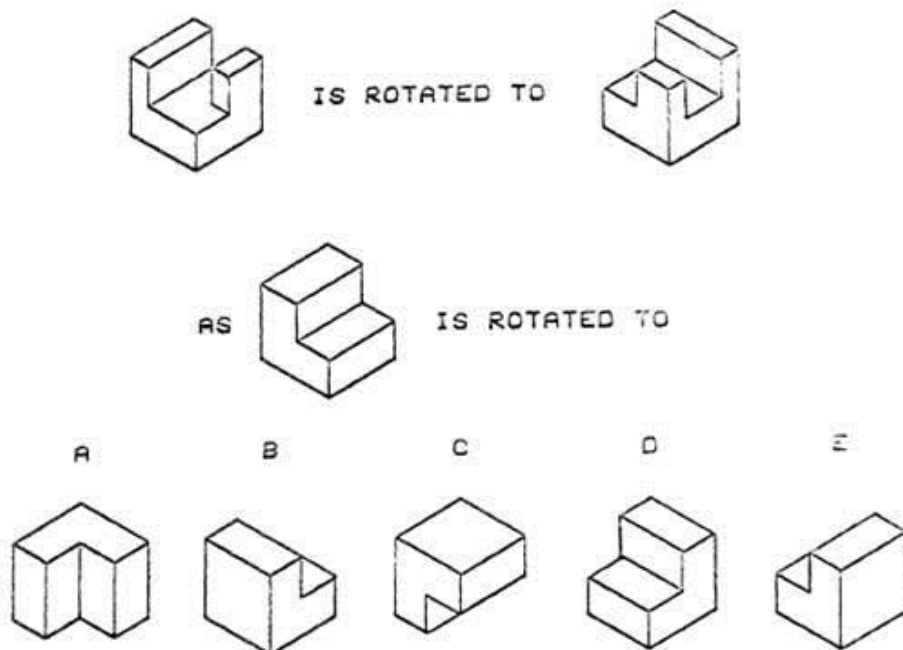


Figure 1: Example Problem from PSVT:R¹⁰. Students taking the assessment are asked to rotate the lower object in the same way as demonstrated for the upper object. Students then select the appropriate response among five multiple choice responses. For this example, the correct response is choice D.

Spatial Skills Assessment and Retention Efforts at Michigan State University

At Michigan State University, we have implemented spatial visualization assessment, specifically the Purdue Spatial Visualization Test: Rotations (PSVT:R), for all members of our first-year engineering class. Implementation was supported by the Engage Engineering project. During academic year 2013-2014, the assessment was undertaken as part of EGR 100, our first-year, introductory design course. Then, beginning in the summer of 2014, students were asked to complete the assessment prior to attending the pre-Fall academic orientation program. Students in both of these groups performing below 60% (17/30 and below) on the assessment were

strongly encouraged (although not required) to participate in a support course, either as an extension of EGR 100 (Academic Year 2013-2014) or as an independent course (Fall Semester, 2014).

Over 2,000 students have completed the assessment to date. As has been shown previously with other student populations¹, female students, on average, have lower scores on the spatial assessment than male students (Males N = 1632, Mean = 22.84, Females N = 392, Mean = 20.29, $p < 0.001$). Their spatial assessment scores correlate strongly with a University-required math placement test that is administered to all students, but the correlation is stronger among females (Males N = 1157, $r = 0.23$, $p < 0.001$; Females N = 232, $r = 0.34$, $p < 0.001$). However, female students outperformed their male colleagues in both EGR 100 (Males N = 1171, Mean = 3.53, Females N = 269, Mean = 3.76, $p < 0.001$) and EGR 102 (Males N = 505, Mean = 3.03, Females N = 158, Mean = 3.27, $p < 0.003$), our first-year, introductory computing course. This suggests that the skills assessed by the PSVT:R and the math placement test are not necessary for success in these courses but, based on the literature, are necessary for success in other courses in the curriculum.

Though limited, our historical data using this assessment have already begun to differentiate among students and their persistence in engineering majors. While male students who have already changed their major out of engineering (“leavers”) performed more poorly on the spatial test than their counterparts that have persisted (“persisters”) (persister N = 880, Mean = 22.69, leaver N = 179, Mean = 21.85, $p < 0.05$), female leavers performed equally to their persister counterparts (persister N = 199, Mean = 19.78, leaver N = 53, Mean = 19.68) (not significantly different). This suggests that the reasons for leaving may be different in these groups, which could also guide our future retention strategies. With enhanced retention as our long-term goal, this paper will describe our initial broad implementation of the spatial skills supplementation curriculum during Fall Semester, 2014 and the results of this course on student performance on the assessment with respect to gender, first generation status, race/ethnicity, and initial mathematics placement.

Implementation of Spatial Skills Supplemental Course

Prior to the beginning of the summer orientation program, students were asked to complete the PVST:R online. For students who were unable to do so, access was provided during their orientation visit to complete the assessment prior to meeting with an advisor to set their first-year schedule. Students were asked to provide consent to have their data used for research purposes. A total of 824 students who took the assessment provided consent--159 women (19%) and 665 men (81%). These percentages are representative of the overall undergraduate student population in our college of engineering. The mean score for women (19.9) was significantly lower than that for men (22.7; $p < 0.001$).

All students with a score < 18 were recruited to enroll in the spatial skills supplemental course. For women, 33.3% scored < 18 , compared with 15.1% of the men. Enrollment in the course was open and voluntary. One hundred twenty-eight students completed the course, including re-taking the PSVT:R as the final exam. Of these 128, 115 had taken the assessment previously in the summer; the remaining students who enrolled in the supplemental course had been admitted prior to implementation of the spatial skills assessment.

The spatial skills supplemental course was offered for the first time during Fall Semester, 2014. The 1-credit course included one lecture (50 minutes) per week. Four sections of the course were offered in a “traditional” classroom with a maximum capacity of 49 students each (198 total). The final enrollment for the course was 128 students. A majority of the instruction was performed by a graduate teaching assistant with some instruction by a lead faculty member. Additionally, two upper-level (senior) undergraduate students served as instructional aides. Their primary role was in assisting with student questions pertaining to homework problems. The aides also performed grading of lecture homework and quizzes.

Materials used for the course included the on-line Engage Engineering Spatial Visualization Skills Teaching Resources Companion Lecture Notes and Quizzes along with the Developing Spatial Thinking text by Sorby from Delmar Cengage Learning. Instruction was supplemented with hand2mind® Snap Cubes with each student receiving 30 pieces of the ¾” interlocking, plastic visual aids. Students purchased the text but were loaned the Snap Cubes pieces for the duration of the course.

The course consisted of a total of 12 weekly sessions with the first being an introduction followed by 10 sessions that used the Engage Engineering lecture materials. The course concluded with the PVST:R administered online on our course management system. Course grades were determined using a distribution of 50% for weekly homework assignments, 25% for daily quizzes, and 25% for the final exam.

Lecture sessions typically began by collection of homework assigned in the previous lecture session followed by a 5- to 10-minute in-class activity. This was followed by a 15- to 20-minute lecture where topics included surfaces and solids of revolution, combining solid objects, isometric drawings and coded planes, orthographic drawings, inclined and curved surfaces, flat patterns, rotation of objects about a single axis, rotation of objects about two or more axes, object reflections and symmetry, and cutting planes and cross sections. Quiz and lecture materials came from the online Engage Engineering Spatial Visualization Skills Teaching Resources Companion Lecture Notes and Quizzes.

Lectures concluded with a number of example problems based on the lecture topic of the day, followed by assignment of the corresponding homework problems. Weekly homework was assigned using problems from the course text. As discussed earlier, homework assigned at the end of a lecture was collected for grading at the beginning of the following lecture session. At the end of a lecture session, the instructor and instructional aides made themselves available to answer student questions as time permitted.

Results from Spatial Skills Supplemental Course

The goal of implementing spatial skills training is to improve students’ retention and performance in engineering coursework. This manuscript is documenting our efforts at implementing the spatial skills assessment and course to assist us in achieving this end. Our initial analysis focused on the success of the course in improving students’ performance on the PSVT:R. Overall, the course helped students substantially and significantly improve their spatial skills as measured by the assessment. The overall pre-test mean for students enrolled in the

course was 14.7, and the overall post-test mean was 21.9 for an average gain of 7.2 points ($p < .001$, paired sample T-test, $n = 115$), with nearly all students improving after taking the course (Figure 2). Multiple students with low pre-test scores (< 10) made improvements at or above the course average. It is important to note that we did not perform a second assessment on any students who did not take the supplemental course. As such, we have no estimate of the magnitude of the repeat testing effect, though this has previously been shown to be minimal for this assessment approach²².

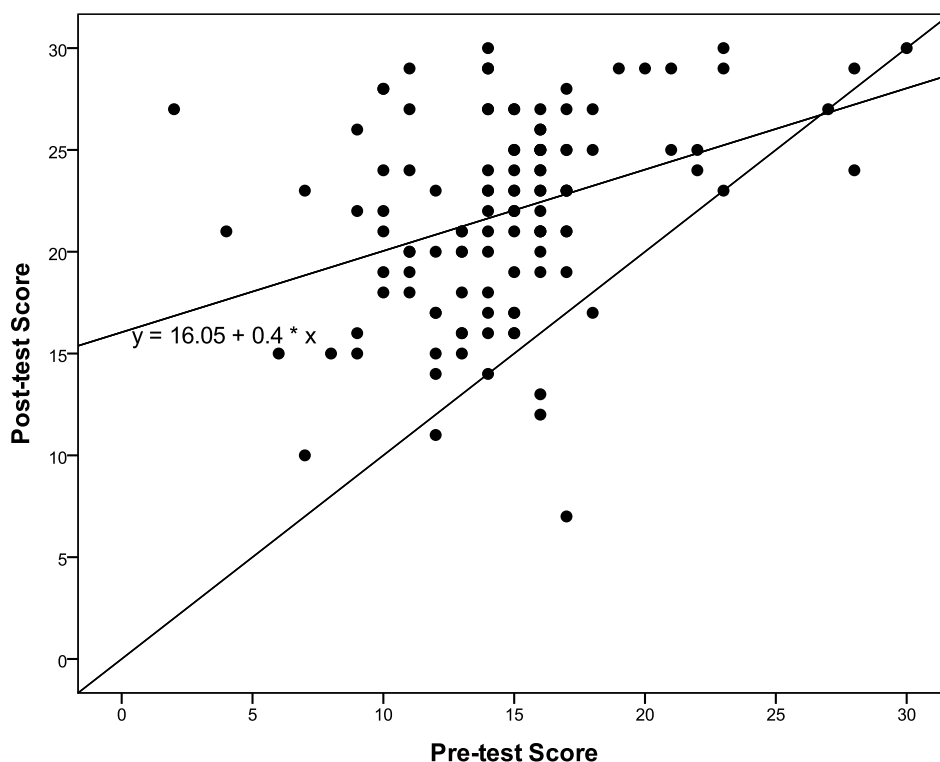


Figure 2: Pre-test vs. post-test scores. Students falling above the 45 degree line had improved post-test scores; students falling below the line had worse post-test scores. The regression line shows the predicted post-test score as a function of the pre-test score.

By looking more closely at the data, we also wanted to determine if the supplementation activities benefitted certain populations significantly more than others. Our results showed that students who started with lower scores had more gain as a result of the intervention (Figure 2). The maximum gain for students scoring > 18 initially was 10 (out of a possible 12). This reflects the ceiling effect for those students who chose to take the course despite above-threshold pre-test scores. The overall maximum gain was 25 (out of a possible 28). It is quite possible that students taking the assessment at home during the summer were not as focused on achieving their best result as when they were in the middle of their first collegiate academic year. An additional explanation could be technical difficulties with accessing the assessment remotely, though students who contacted us with this issue had their assessments reset and were allowed to restart/retake the assessment upon arrival at orientation.

Women v. Men

As we saw in our analysis of all of our 2014-2015 assessment data, men did better than women overall on the pre-test. However, of the students who enrolled in the course, the average pre-scores were 14.4 for the women (n = 41) and 14.9 for the men (n = 75) (not significantly different). The average post-scores were 22.0 for women (n = 43) and 22.7 for men (n = 85) (also not significantly different). This was encouraging as it reinforced that, as regards gender, everyone benefitted equally from the supplementation activities.

First Generation

This similarity in impact holds true as well when examining first-generation status. At MSU, students self-report first generation status during the application process, making it difficult to ensure uniform interpretation of who is and is not a first-generation college student. Regardless, the reporting is an official demographic datum used by the university registrar. Therefore, we compared the performance of first-generation students (FG) with those who were not first-generation (NFG). The average pre-scores were FG, 14.6 (n = 38) and NFG, 14.8 (n = 78) (not significantly different). The average post-scores were FG, 21.2 (n = 40) and NFG, 22.7 (n = 88). The post-scores were also not significantly different.

Race/Ethnicity

While our data set was too small to compare each ethnicity group, previous studies on mathematics performance of our incoming student populations indicate that African American and Hispanic students score similarly, and Asian and White students perform similarly (unpublished data). We therefore combined these groups of students and compared the change in assessment performance for African American/Hispanic (n = 29), Asian/White (n = 63) and Blank/Missing ethnicity (n=23) by ANOVA; again, there was no difference across groups (df = 2, 112).

Interactions

To look for interaction effects, we performed a regression analysis to predict the post-score based on pre-score, MSU math placement score, gender, first-generation status, and ethnicity. Overall the regression equation accounted for 15% of the variance in the post-score ($p < 0.001$). However, only the pre-score ($\beta = .274$, $p < .005$) and math placement score ($\beta = .268$, $p < .021$) were significant. Based on these analyses, we conclude that gender, first-generation status, and ethnicity were not related to student outcomes in the supplemental course.

Research by others has shown a correlation between spatial skills and math performance². For students in our course, the pre-test scores correlated with the university's math placement test, which is used to determine which math course students should first take ($r = 0.245$, $p < 0.02$). Students' scores on the post-test also correlated with the math placement score ($r = 0.359$, $p < 0.001$), but there was no correlation between the math placement score and students' improvement on the spatial skills assessment ($r = 0.1$, $p > 0.3$). Since the math placement score will determine a student's first math course, we compared the **changes** in spatial assessment scores across students who were enrolled in different math courses. The courses with sufficient

numbers of students for analysis were Intermediate Algebra (n = 15, mean change = 7.6), College Algebra (n = 10, mean = 5.1), College Algebra and Trigonometry (n = 33, mean = 5.9) and Calculus I (n = 36, mean = 8.4). We performed an ANOVA on the means, which was not significant (df = 3, 90; $p < 0.17$). In addition, none of the post-hoc tests of the pairs of means were significant. Thus, student scores improved similarly, regardless of which math course they were taking.

Given our prior analyses showing that MSU students who leave engineering often do so at the end of the semester in which they took Calculus I (unpublished data), it was of interest to determine if spatial skills training could lead to improved performance in Calculus I. We compared students with an incoming spatial skills score ≤ 17 who took Calculus I in Fall Semester, 2013 with NO intervention (n = 44, mean grade = 2.6) with students taking the spatial skills course in Fall Semester, 2014 with incoming scores ≤ 17 who took Calculus I (n = 26, mean grade = 2.7). Given the sample sizes, we could identify no significant difference between the two populations. We also performed regressions to predict the students' math grade for each math course based on their math placement score and pre- and post-test spatial assessment scores. With our current sample sizes, none of the models was significant.

Conclusion

Taken together, our results make clear that spatial skills training can improve our students' performance on the PSVT:R. Moreover, regardless of initial score, gender, first-generation status, ethnicity, and math placement, all students benefitted equivalently from the supplemental course. At this point, we cannot yet state whether strengthening students' spatial skills will improve their success and persistence, but we will continue to track these students to better quantify any effect. Our first significant opportunity to assess an effect will be the students' admission to the College of Engineering. As stated above, we have considerable interest in understanding if different factors influence retention in different student populations. Going forward we anticipate pairing our spatial skills assessment and demographic data with student self-efficacy data as a means of refining our analysis of student persistence.

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