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# The Next Frontier: Integrating Spatial Reasoning into a First-Year Engineering Course

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# The Next Frontier: Integrating Spatial Reasoning in a First-Year Engineering Graphics Course

The construct of spatial reasoning encompasses our abilities to solve problems of navigation; recognize relevant spatial patterns or details; and visualize objects from different angles (Paultanis, 2014). Scholars have disagreed with the scale and scope of what the term includes, but they do agree on the significance of a deeper understanding of how we develop our ability to think spatially. This recognition resulted in a significant body of research and practice at all levels of education, ranging from infants to senior citizens. This study represents one instructor's efforts to apply that cumulative body of knowledge to strengthen spatial reasoning abilities of students enrolled in a large, first-year Engineering Graphics course.

Researchers have noted that K-12 students with strong spatial reasoning abilities tend to gravitate towards STEM fields and these abilities are more predictive of college enrollment than other measures reflected in standardized testing, such as SATs (Park et al., 2010; Wai et al., 2009; Webb et al., 2007). The effect appears to weaken as the student approaches mastery, and the degree to which such abilities are sufficient or necessary for advanced work across all STEM fields remains unclear. In engineering, however, spatial reasoning has been identified as a core competency for students at both the K-12 and university levels (ABET, 1998; Barr, 2012).

Researchers are still exploring what factors may contribute to students' abilities to reason spatially. Previous research on gender gaps has proven to be inconclusive, but other factors such as childhood play, video gaming, and early interventions appear promising (Gold et al., 2018). What is clear is that interventions during the first-year of college are not only effective in strengthening the spatial reasoning ability of most students; but also, such interventions are likely to have positive effects on a number of undergraduate student success markers, including persistence, across STEM disciplines (Duffy et al., 2015; Sorby, 2001).

**The Intervention**: Starting in 2000, the engineering graphics course that is the focus of this study followed the standard pedagogical model in which students moved from simple drawings to more complex solid modeling using computer aided design software such as AutoCAD and Inventor (Hsi et al., 1997). The instructor would demonstrate the approaches step-by-step during the recitation sections and students would be asked to duplicate and/or apply what they had learned from the demonstration in dedicated lab sections. The format had the advantage of being scalable, which allowed enrollment in the course to more than double over a five-year period. As of 2017, there were a number of indicators that the format needed to be revised. These included an increasing number of students receiving a grade of D or F and those who withdrew (DWF rates), declining examination score averages and a lack of student engagement, as noted through classroom observations. Perhaps most painfully, the need for change was also evident in the student evaluations of instruction, which indicated, among other feedback, that students struggled to perceive the relevance of the skills being taught in the course. To address this feedback, the instructor chose to make significant changes to the design of the course. In the first iteration of the course design, class time was devoted largely to instructor-led demonstrations and student practice limited to the laboratory sections of the course. Pedagogically, the separation rested on the assumption that students would need to have these skills modeled by an expert before they could apply it for themselves in the lab sections. With the availability of video tutorials and other support resources that students could access from increasingly ubiquitous devices; the instructor chose to collapse the differences between the lecture and lab sections; shifting the need for demonstrations and the related development of technical, software skills to a technology-mediated, on-demand model.

The shift in delivery mode for skill-based instruction led to the opening up of class time that could be devoted to other activities, including some that had previously been relegated to the labs as well as new applications. The instructor chose to increase the experiential components of the course and provide more opportunities for students to practice their spatial reasoning skills, the majority of which did not require access to proprietary software. To this end, she devised a series of low-stakes/ungraded exercises that required only simple manipulatives, such as blocks or worksheets, and allowed the students to increase their mastery while working together in small groups, the latter of which supplemented instructor-led teaching with peer learning. In the revised model, students watch an abbreviated demonstration, then work through 2-4 iterations of practice exercises while being provided multiple opportunities to ask questions of the instructor, walk around and compare their results to those of classmates, and/or reference exemplars provided through the course's learning management system (LMS), accessible through their mobile devices. The practice exercises progressed in complexity from recognizing the correct view from an example rotation of an object to drawing a correct missing view given other views of the object. This study was devised to assess how effective these strategies were in enhancing the ability of engineering students to exercise spatial reasoning.

**The Study**: Our study was conducted at Tennessee Tech University, a medium-sized, STEM-focused, level-1 doctoral granting institution located in the suburban southern region of the United States. The College of Engineering is the largest college at the university and the number of undergraduate majors has grown significantly over the past five years. Data were collected from all students present and enrolled in ENGR 1110: Engineering Graphics for Fall 2017. This is a large-enrollment, introductory course, required by four majors in the college, and students are encouraged to take it in their freshmen year. The pre-test included 112 undergraduate students. In this population, 99 students were males and 13 students were females; 73 (65%) of whom were freshmen. Outside of class standing, the identified demographic characteristics of the class are roughly representative of the overall population of students in the college.

**The Instrument**: The study utilized a pre- and post- survey to measure student's abilities to engage in spatial reasoning. There are a number of pre-existing instruments designed to assess spatial intelligence, most notably the Purdue spatial visualization test (PSVT), a validated psychometric measure which has been frequently used to assess the first-generation of spatial reasoning pedagogy in engineering (Olkun, 2003; Sorby & Baartmans, 2000; Sorby, 2009). As cognitive understanding of spatial reasoning has evolved, however, researchers have called for new instruments to capture its complexities (Ness et al., 2017). The Purdue test focuses on one aspect of spatial reasoning, visualization, and lacks explicit connection to creative problem solving required specifically of engineers. For these reasons, the researchers chose to develop a new survey designed to focus on both lower and higher-order applications of spatial reasoning in an engineering context.

The proffered assessment consisted of six items, four multiple-choice questions and one constructed response question. To maximize participation, students completed the assessment on paper during regular class time, under the supervision of an IRB-approved external moderator. No incentives were provided to induce participation and all responses were recorded anonymously. The results of the pre- and post- assessments were triangulated with other student success data collected from the course. Such mixed methods approaches have demonstrated promise and yielded new insights in other studies of spatial reasoning with undergraduate students (Ormand et al., 2013).

**The Method**: The researchers scored the pre- and post- tests, with one point for each correct choice made in the first four multiple-choice questions; and six points possible for each correctly identified feature in the final question. The pre-test was given to 112 students with a mean score of 4.955. The post-test was given to 84 students with a mean score of 8.881. The difference in the mean scores showed a gain of 3.926 in the post-test scores. Due to the lower number of students taking the post-test, equal variances among the mean cannot be assumed as shown by the significance value lower than 0.05. For that reason, equal variances cannot be assumed according to Levene's Test for Equality of Variances. An independent-samples t-test was conducted to compare the results from the pre-test and the post-test. The difference of 3.926 is a significant increase from the pre-test to the post-test, $t(183.175) = 17.714$, $p = 0.000$. These results suggest the changes made to increase spatial reasoning abilities in the Engineering Graphics course contributed to the gains made in student performance.

**The Findings**: Our data suggest that the interventions have led to improvements in students' spatial reasoning skills (see Figure 1). There is further indication that these benefits extend from lower to higher order thinking. When the questions are ordered according to level of challenge, it can be noted that the students' composite score drops as the questions become more complex in both the pre- and post- tests, but the slope changes in the post-tests. As the difficulty of the questions increase, the improvement from pre-test to post-test is more significant.

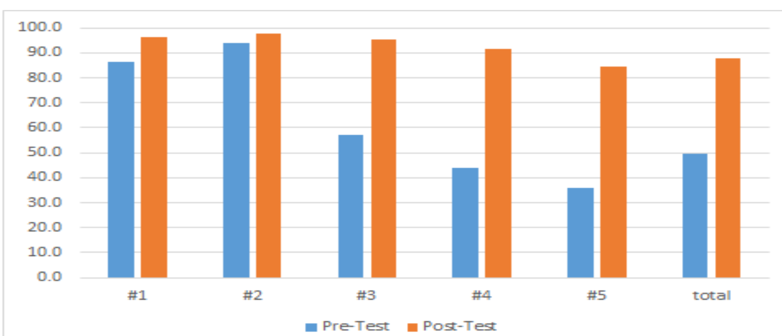


**Figure 1. Composite Pre- and Post-Test Scores by level of Difficulty**

Our findings further suggest that the students improved their capacity for spatial reasoning. The fifth item on the assessment required the students to draw in a missing view of a provided object; and points were awarded based on their ability to identify six features of the object and represent them appropriately. To successfully complete this exercise, students need to not only be able to visualize the object, but also to imagine the hidden features and to construe them on paper;

thereby integrating three primary spatial reasoning skills. In the pre-test, 48% of the students were not able to complete the assignment successfully; for the post-test, 53% of students could draw the missing view with no more than one improperly represented feature (see Figure 2).

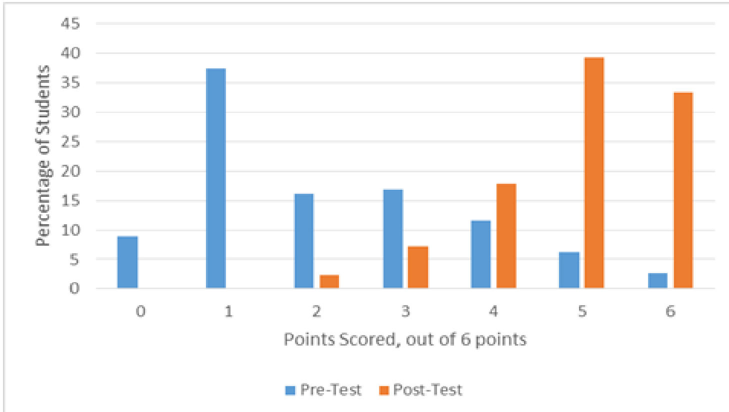


**Figure 2. Pre- and Post- Point Distribution for Assessment Item 5**

Our findings suggest that some students increased their ability to retain mastery of spatial reasoning as a result of the interventions. It should be noted that the sample size for the pre-test was 112 students while the sample size for the post-test was 84 students, a reflection of a 24% DWF rate for the course. Relative to other disciplines, this percentage appears high, but it is not incompatible with broader trends for large-enrollment STEM courses. It is disappointing that the new design, at least in its first iteration, did not contribute to higher rates of success for these students at the bottom of the scale, but there is reason to remain hopeful. Further analysis of grade distributions of the course revealed that 53% of students in the course received either an A or B as their final grade, a noticeable improvement over previous course offerings. Their success moved the overall grade distribution much closer to a Gausian curve at the top of the distribution than any previous iteration of the course (see Figure 3).

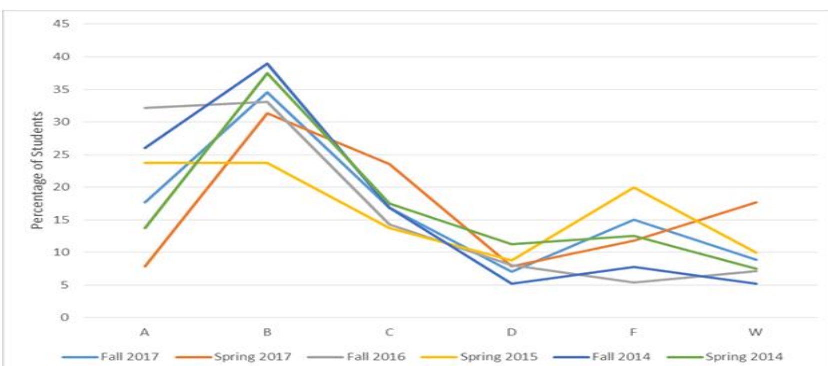


**Figure 3. Final Course Grade Distribution (single instructor)**

Previous studies established a possible link between spatial reasoning abilities and long-term student success. Our study affirms this connection. The researchers looked at projected enrollment in the major to determine which of the lower-performing students from the course persisted in the same academic year (see Table 1). Our analysis demonstrates that students who received a passing, but low, grade in the course, appear to be satisfied with their performance and have chosen not to repeat it, at least in the short term, but all remain enrolled in the same Engineering major. Of the students who withdrew (n=9), the majority (n=5) remain enrolled at the university, though not necessarily as engineering majors. Of those who failed (n=17), 59% (n=10) have chosen to repeat the course. It may prove interesting to conduct follow-up studies that follow the persistence of these students through to graduation, perhaps even beyond.

**Table 1. Persistence Data for Low-Performing Students**

| | | **Engineering Majors** | | | | **Other Majors** | | |
|---|---|---|---|---|---|---|---|---|
| | Total Students | Students | Still Enrolled | Students repeating | Left the College | Students | Still Enrolled | Students repeating |
| **D** | 6 | 5 | 5 | 0 | | 1 | 1 | 0 |
| **F** | 17 | 15 | 11 | 9 | 1 | 2 | 2 | 1 |
| **W** | 9 | 4 | 1 | 1 | | 5 | 4 | 0 |

**Discussion**: Persistence is often negatively correlated with class size; with lower levels of student-faculty engagement playing a significant role in student motivation (or lack thereof). As this case demonstrates, the challenges of developing pedagogies of scale are myriad, but they do not necessarily have to work at cross-purposes with the integration of inductive teaching methods, including those designed to foster spatial reasoning. While increasing the use of pen and paper drawing may seem like taking a step backward, the increased integration of technology-mediated delivery of skill-based instruction allows more classroom time to be devoted to activities that are not as well suited for technology-mediation (such as hand drawing) or that maximize student engagement, whether with the instructor or each other. This intervention does not solve the complex problem of student engagement in large-enrollment courses, as is evident in the number of students with low attendance in this study, but perhaps it gets us one step closer.

The solutions may lie outside the scope of a single class. In a recent research report the American Council on Education indicated transformation in STEM education should be moving to the programmatic level. Their findings emphasize a need for change to take place at a larger scale encompassing multiple levels of the undergraduate curriculum. In our intervention, we supplemented skills-based scaffolding with cognitive scaffolding; and this resulted in demonstrable impact on student learning outcomes. It may be possible to consider similar scaffolding across the engineering curriculum; but this kind of cognitive mapping runs the risk of eliminating the need for a separate graphics course focused primarily on a set of defined skills. In other words, our study, though ostensibly a success, may have the long-term effect of arguing our course out of existence.

The psychometric tests commonly used to measure spatial ability, such as the PSVT, have limitations in their applicability to fully capture all stages of spatial reasoning. The instrument developed for this study is itself vulnerable to questions of content validity. Although the questions used in both the pre- and post-test were not identical and efforts made to ensure that equity in degree of difficulty, we did not control for the resemblance between the test items and the in-class examples used by students nor for their exposure to instruction related to spatial reasoning in other courses, including those taken prior to enrolling in college. That said, engineering educators are not alone in seeking stronger assessment measures of spatial reasoning. Unlike the development of technical skills, engineering shares the challenge of fostering spatial reasoning in undergraduate students with multiple disciplines, including non-STEM fields such as graphic design, architecture and even medicine. The recognition of this, and other similar, shared challenges in teaching and learning have the potential to lead to increased inter- and multi- disciplinary conversations about teaching, learning and research.

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