Paper ID #18070

Applied Spatial Visualization for Engineers

Mrs. Agata K. Dean, Colorado School of Mines

Agata Dean graduated from Colorado School of Mines with a BS in Mechanical Engineering in 2004, and a Masters in Math in 2006. She taught in the Mathematics department at Mines for 10 years and now teaches spatial skills through the Center for Academic Services and Advising. She also serves as the faculty advisor for the largest collegiate section of the Society of Women Engineers at Mines.

Applied Spatial Visualization for Engineers

Introduction

Spatial visualization is widely recognized as an important skill for engineering students, often being an indicator to a student's success in engineering classes and retention in engineering programs.[1-4, 6] At Colorado School of Mines, efforts have been made over the past several years to launch a course designed to improve spatial skills among students who test poorly in this area. The course has evolved significantly over the past four years with major efforts aimed at enrolling first and second year students, providing intense and efficient spatial skill development opportunities, and encouraging an understanding of the broader implications of strong spatial skills. This paper describes the evolution and results of these efforts.

Background

While it is recognized that spatial visualization is an important skill, especially for engineering students, many first year students enrolled in engineering programs around the nation struggle with spatial skills, as tested by the student's performance on the Purdue Spatial Visualization Test: Rotations (PSVT:R).[8] The PSVT:R test has been shown to be a significant predictor of success in engineering graphics courses.[1-4] Research has shown that spatial skills can be learned with practice.[3, 6, 8, 9] To this end, various interventions aimed at improving struggling students' spatial skills have been done at institutions around the country,[2, 4] with the primary instruction tool being the "Developing Spatial Thinking" workbook.[3, 5, 6] For the purposes of this intervention, a score of less than 70% (20 or fewer out of 30 questions answered correctly) on the timed, multiple choice PSVT:R test is the indicator used to determine whether a student "struggles" with spatial skills.

A spatial skills course was first offered at Colorado School of Mines in spring 2014, bearing no course credit. It was then approved as a one-credit hour course titled CSM 151, to begin in spring 2015. In June 2016, an intensive course revision initiative was offered at Colorado School of Mines for faculty hoping to improve student learning in their course, grown out of a study on transforming teaching and learning.[7] Within this context, the CSM 151 course was significantly redesigned to address specific concerns with the way the course was run prior to Fall 2016. The three major areas of concern for the redesign effort are summarized in Table 1. This paper describes the efforts to reach the target population, promote multidisciplinary connections, and provide a novel curriculum developed around the course workbook[5] and designed to enrich student learning at Colorado School of Mines.

Table 1: Significant Revisions to CSM 151 Implemented in Fall 2016

Target Topic	Proposed Solution
Improve Course Structure	Design in-class activities to develop aspects of spatial visualization and move workbook to out-of-class homework
Promote Multidisciplinary Connections	Introduce a team research project to explore the role spatial skills play in another field of interest to the students
Enroll Students from Target Population	Email incoming first year students, encouraging them to take the PSVT:R pre-test and register for the class if they score less than proficient; open additional sections of the course in late summer when first year students register for classes

Methodology
The first major revision to CSM 151 addressed the overall course structure. Minor changes in the course structure evolved over time, with a major shift occurring in Fall 2016. Table 2 summarizes the evolution of the course structure each semester.

Table 2: Summary of Course Structures

Semester	Course Details	In-class Structure	Out-of-class Homework
Spring 2014	Pilot course, no credit, 10 weeks, 3 hour class, optional attendance	10-15 minute lecture, up to 2.5 hours to work on workbook and ask questions, quiz when finished	Finish workbook if necessary (rare)
Spring 2015	1 credit hour free elective course, 11 weeks, 1 hour per week in class	10-15 minute lecture, up to 30 minutes to work on workbook and ask questions, quiz when finished	Finish workbook module
Spring 2016	1 credit hour free elective course, full semester length (15 weeks), 1 hour per week in class	Up to 10 minutes for quiz on previous week's module, 10-15 minute lecture on new topic, up to 30 minutes to work on workbook and ask questions	Finish workbook module
Fall 2016	1 credit hour free elective course, full semester length (15 weeks), 1 hour per week in class	10-15 minute lecture on new topic, in-class activity to support concepts; two in-class exams	Complete entire workbook module

In the first few semesters, students would listen to 10-15 minutes of lecture on one module in the workbook and then spend the majority of in-class time working on their "Developing Spatial Thinking" workbook. The reasoning for this structure was to allow students to ask the instructor for help if they needed it. In the original pilot course, which was offered in an evening workshop style, students had three consecutive hours dedicated to the class each week. This allowed them sufficient time to complete the entire workbook section and end class with a quiz.

Once the course was approved as a one credit hour elective, the same structure was used for spring 2015; however, with only one hour in class each week, students were told to do a few problems of each "type" in the workbook section for that class session, so they could practice enough to complete the quiz at the end of class. It was understood that students would not have enough time to complete the entire section during the allotted class time.

After receiving formal and informal student feedback, the order of course activity was changed for spring 2016: each class began with a quiz over the previous week's module. Moving the quiz to the beginning of class meant all students had sufficient time to study the material from the previous week before being tested on it. However, the amount of time needed for students to complete the quiz varied, so some students felt rushed while others sat bored, waiting for the lecture to begin. With time, it became evident that many students came to class to complete the quiz, stayed for the lecture, and then left class because they had already completed the workbook on their own. Additionally, the majority of students did not ask questions or interact with their peers while working on the workbook. Finally, the success of the course, measured by an increase from pre-test to post-test on the PSVT:R, was lower than desired. While the average increase from pre-test to post-test was consistent with what has been seen at other institutions,[3, 6] a disappointing number of students were still unable to pass the PSVT:R after completing the course. These three pieces of evidence made it clear that instructional time was not being utilized as effectively as possible.

Research shows that a variety of formal and informal experiences and activities can boost a student's spatial skills.[2] Using the evidence gathered in the first three spring semesters of teaching CSM 151, a decision was made to move workbook exercises out of class, and utilize in-class time on activities that could not be done individually. This effort has resulted in a novel curriculum based on the workbook. The weekly in-class activities support the instruction in the modules of the "Developing Spatial Thinking" workbook, without repeating the exercises in the workbook, and a portion of the student's grade is based on participating in these activities. Table 3 shows a select few of the activities that have been developed to supplement the workbook.

Table 3: Sample In-Class Activities Implemented in Fall 2016

Workbook Topic	In-Class Activity
Combining Solid Objects	Students work in pairs to solve tangram puzzles and answer a series of questions regarding how these puzzles relate to the operations of combining objects – cut, join and intersect.
Orthographic Sketching	Students work in groups of three to place objects of various difficulties in an Ortho-Box™ and draw the views directly on the top, front and sides of the Plexiglas panes, which then unfold into the orthographic views.
Flat Patterns	Students work in small groups to cut and fold various paper patterns and then discuss trends and tips to more quickly identify whether or not a flat pattern would create a closed object.
Rotations About Multiple Axes	Students learn algorithms used to solve a Rubik's cube and analyze how and why those algorithms work.

After participating in the in-class activities, the students apply these skills outside of class as they complete the workbook section as homework. The workbook is collected at the beginning of each class, and the previous week's section is checked for completion and accuracy. Twice during the semester, the students take an individual in-class exam. The intentions of these changes were two-fold: to increase student engagement in the course, and to increase students' spatial skills as measured by the PSVT:R. An increase (of any amount) from pre-test to post-test is also factored into a student's overall course grade. A breakdown of the grading structure is shown in Table 4. The results of the changes implemented for Fall 2016 are discussed in the final section of this paper.

Table 4: Grade Breakdown in CSM 151

Category	Portion of Final Course Grade	Description
Participation in In-Class Activities	25%	Each weekly assignment is equally weighted and all students receive full points for completing the activity regardless of accuracy or quality.
Completion of Workbook	20%	Each of the ten workbook sections are equally weighted at 10 points, with 6 points for completion and 4 points for accuracy (on four pre-selected, representative exercises).
Exams	20%	Two exams, equally weighted at 10% each; the first exam covers the sketching and 2D portions or the workbook while the second exam covers the rotational and symmetry aspects.
Research Project	25%	Four assignments are factored into this team project – a one page proposal, a three page status update, a rough draft and the final presentation done in class. Individual grades are weighted based on a team's self evaluation.
Demonstrated Improvement	10%	This portion of the grade is an "all or nothing" based on whether the student has increased their PSVT:R score from pre-test to post-test.

Promote Multidisciplinary Connections

Student feedback from the first three semesters often included comments that indicate, at best, a superficial understanding of the importance of spatial skills in various engineering undergraduate classes, such as Calculus, graphics, and engineering design studios. Comments such as "class … made me able [to] visually see transformations much better," "I feel like I am much more prepared for Calc 3" and "it will definitely help me in the long run" show that students are able to see the immediate implications of the spatial skill development, but are not able to express the specific or tangible connections to other aspects of their lives or their futures. Despite explicitly stating these connections in communication to students prior to registration week and in the first week of class, low enrollment in CSM 151 suggested that students – especially first and second year students – while they did seem to enjoy the class, did not understand the potential benefit of taking the class.

In order to underscore the explicit connections between spatial skills and other undergraduate engineering courses, careers and industries, a team based research project was introduced in Fall 2016. The reasoning behind this addition was to encourage students to look more deeply at some class, field, or hobby they were interested in, and explore the connections between that topic and spatial thinking. The students then report their findings to their classmates in the form of a final team project presentation. Less formally, the hope was that students who had this deeper understanding of the benefits of spatial skills instruction would then become ambassadors to other students, encouraging them to take the class to better prepare them for successful engineering pursuits. In Fall 2016, student research projects included topics such as the importance of spatial understanding in sports (strategizing a football play, designing a football helmet to decrease concussion rates), in petroleum engineering (an understanding of subsurface elements, interpretation of topological maps, drilling efficiencies), and in the medical field (chirality of molecules, surgical practice, physical therapy), among many others.

Addressing the Target Population
The first time Colorado School of Mines planned to offer a spatial skills course, student members of the collegiate section of the Society of Women Engineers (SWE) were emailed. Research suggests that females are more likely to struggle with spatial skills than males,[1-4, 6] and the SWE section provided a large population of potential students. The email to SWE members specifically addressed first and second year students, encouraging them to hone their spatial skills by participating in this voluntary workshop. In spring 2014, eight students, all first year females, chose to participate in the pilot program; seven of the eight students scored below 70% on the PSVT:R pre-test. Over the course of the three spring semesters in which the course was taught, the percentage of students taking the class who fit in the target population – first year engineering students struggling with spatial skills – dropped significantly: from 100% first years the first semester down to 14% first years in Spring 2016, and from 80% struggling the first semester down to 67% struggling in Spring 2016. Consequently, it was determined that efforts should be made to better attract the target population.

A campus-wide change in the registration process for first year students facilitated the desired changes and successfully impacted the population of students enrolled in CSM 151 in Fall 2016. During registration in Spring 2016, one section of CSM 151 was offered for the following fall, and was filled primarily with seniors who needed to fulfill a one-credit hour free elective requirement. In summer 2016, incoming first year students were encouraged to take the PSVT:R pre-test to determine their spatial ability. Of the 912 students (91% of the incoming class) who took the pre-test, 25% scored below the chosen proficiency threshold. These numbers indicate that spatial skill development is a crucial intervention. Additional sections of CSM 151 were opened and these students were encouraged via email to enroll; in all, in Fall 2016, 34 students chose to take the course. Of these students, 64% were first years and 92% of the students are identified as struggling with spatial skills.

Results
The primary intention of the three modifications made in summer 2016 was to increase students' spatial ability as measured by their performance on the PSVT:R pre-test and post-test. In order to validate the educational impact of the changes that were made, the results of the PSVT:R test were initially analyzed in two ways – the number and percentage of students able to pass the PSVT:R, and the mean student increase from pre-test to post-test.

Table 5: Summary of Results

Semester	N	Mean Pre-Test Score (out of 30)	Pre-Test Passing Rate (number of students)	Mean Post-Test Score	Post-Test Passing Rate (number of students)	Mean Increase
Spring 2014	8	16.0	12.8% (1)	23.5	87.5% (7)	7.5 (58.0%)
Spring 2015	19	20.4	63.2% (12)	26.9	94.7% (18)	6.5 (61.2%)
Spring 2016	19	18.4	26.3% (5)	26.0	84.2% (16)	7.6 (58.4%)
Fall 2016	34	16.4	8.8% (3)	26.8	97.1% (33)	10.4 (73.2%)

The data in shown in Table 5 summarizes the results of the PSVT:R and suggests a positive outcome to the intervention. An increased pass rate on the post-test over prior semesters would indicate success of the changes that were made. When spatial skill development in the course was based solely on the workbook, the exposure to spatial thinking did boost student scores from pre-test to post-test. However, the gains appear to be more dramatic after the modifications made for Fall 2016.

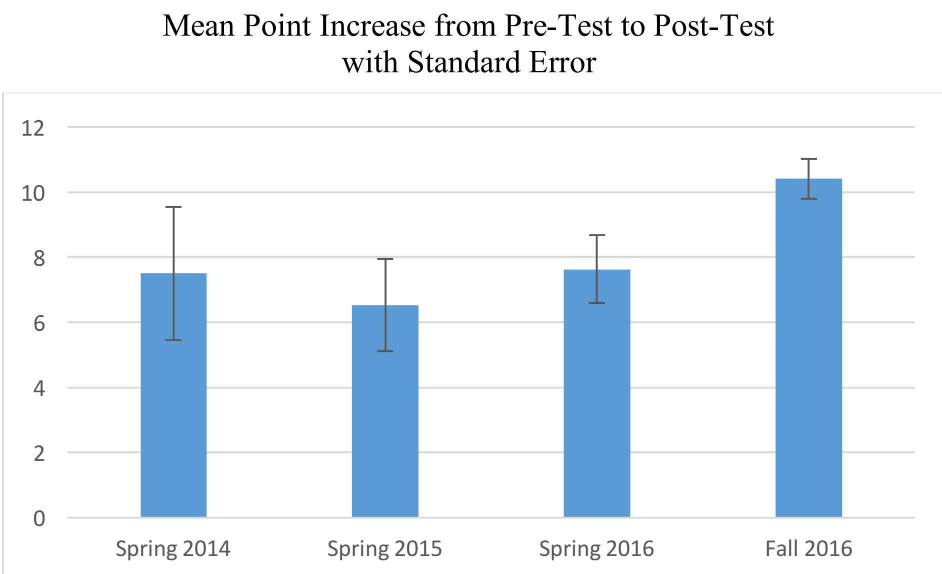

Figure 1: Mean Point Increases

As seen in Figure 1, the mean point increase from pre-test to post-test after the course restructure is noticeably higher than the growth during the first three semesters in which the spatial skills course was taught. To determine whether this outcome was statistically significant, an ANOVA test was used on the four semesters of data. The results of the ANOVA yielded $p = 0.025$, suggesting that there is a statistically significant difference between at least one pair of the mean increases. Comparing the mean point increase between each pair of semesters using t-tests with a Bonferroni adjustment showed that there was no statistically significant difference in the mean point increase between any pair of the first three semesters (the three "pre-intervention" spring semesters). This result justified grouping the three spring semesters into one data set.

After grouping the data into pre-intervention and post-intervention data sets, a null hypothesis was stated that the mean point increase after intervention (Fall 2016) was lower than the mean point increase prior to intervention. Running a t-test yielded a t-statistic of -3.267, which suggested that the null hypothesis can be rejected with $p = 0.0008$. In other words, there is statistically significant evidence that the mean point increase after intervention is higher than the mean point increase before intervention.

One concern in looking solely at the pre-test and post-test scores is the validity in attributing the increase to the spatial skill intervention rather than test familiarity or learning spatial skills from another method, such as freshmen engineering courses. Certainly it can be expected that some increase would occur over time even without formal spatial skill education, though research suggests the increase is generally minimal.[3] While the data sets are small, it is valid to assume the intervention had a marked impact on spatial skill development for the population needing it, because the increases seen from pre-test to post-test in the first three semesters were consistently near 60% (which is consistent with such interventions elsewhere in the US[6]), while the increase from pre-test to post-test after the course restructure was more than 70%. This jump in the growth of students' spatial skills can reasonably be attributed to the increased spatial skill instruction beyond what was seen in previous semesters. Ideally, a group of students who took the PSVT:R and chose not to take CSM 151 would be asked to take the PSVT:R again as a post-test to be considered as a control group. However, without offering some incentive for students to take a post-test without taking the class, it has not been feasible to get these control group data on a large enough scale.

A secondary positive outcome worth noting in Table 5 is that the growth in the number of students enrolled in CSM 151 is on a positive trajectory. While the course remains small, and certainly does not include all students who could potentially benefit from spatial skill development, enrollment has been increasing steadily. CSM 151 remains an elective course, with no plans of becoming mandatory due to various institutional decisions, so any growth in enrollment is a positive sign that the community values the instruction and understands its potential benefits.

Finally, the lower average pre-test score and low percentage of students passing the pre-test in Fall 2016, compared to prior semesters, is an indicator of better reaching the target audience. Much of this can be attributed to the change in how registration occurred, specifically the fact that sections of the course were opened in the summer, after upperclassmen had already registered, to encourage first year students to enroll in the class. This is something that can easily be done in preparation for the fall semester, but is much more difficult before the spring semester. It should be mentioned that enrollment in Spring 2017 reverted back to the demographics of prior spring semesters – of the 26 students enrolled, only 38% are first year students (and 46% are seniors), with an average pre-test score of 21.3 and half of the students having already achieved a passing rate on the pre-test. Continued efforts are necessary to ensure that the target population is reached in both fall and spring semesters.

Conclusion

The CSM 151 course has evolved since its inception at Colorado School of Mines. Continued endeavors are being made to attract more first year students in both fall and spring semesters. For next fall, it is likely that incoming first year students will once again be encouraged to take the PSVT:R pre-test before they arrive on campus. It may be possible that when the registrar's office builds these students' schedules, they could automatically enroll students in CSM 151 if they do not pass the PSVT:R pre-test. Students would have the ability to "opt out" of the course, but evidence suggests many students may choose to remain enrolled, especially with the help of concerted communication efforts regarding the value of spatial-visual skills in engineering courses and professions.[2, 3] In addition to continuing efforts to enroll more students within the target population in the course, we will continue gathering data to support innovation in the delivery of instruction. Efforts will also be made to gather control group data.

References

1 Bairaktarova, Diana, Matthew Reyes, Nooshin Nassr, and Dan Thomas Carlton, "Identifying Motivational Factors and Lived Experiences that Enhance Spatial Skills in Novices and Experts in STEM Disciplines," American Society for Engineering Education, 2015.

2 Metz, Susan Staffin, Susan Donohue, and Cherith Moore. (2012) "Spatial Skills: A Focus on Gender and Engineering" In B. Bogue & E. Cady (Eds.), Apply Research to Practice (ARP) Resources. Retrieved January 31, 2017 from http://www.engr.psu.edu/AWE/ARPResources.aspx

3 Segil, Jacob L., Beth A. Myers, Jacquelyn F. Sullivan and Derek T. Reamon, "Efficacy of Various Spatial Visualization Implementation Approaches in a First-Year Engineering Projects Course," American Society for Engineering Education, 2015.

4 Sorby, Sheryl, "Developing 3-D Spatial Visualization Skills," Engineering Design Graphics Journal, 1999.

5 Sorby, Sheryl, "Developing Spatial Thinking" workbook, Delmar, Cengage Learning, 2012.

6 Sorby, Sheryl A., "Educational Research in Developing 3-D Spatial Skills for Engineering Students," International Journal of Science Education, 31: 3, pg 459 - 480, 2009.

7 Spiegel, Sam, Stephanie Claussen and Renee Falconer, "Insights into Systemically Transforming Teaching and Learning," American Society for Engineering Education, 2016

8 Stieff, Mike and David Uttal, "How Much Can Spatial Training Improve STEM Achievement?" Educational Psychology Review, DOI 10.1007/s10648-015-9304-8, Springer Science+Business Media New York, 2015.

9 Uttal, D. H., N. G. Meadow, E. Tipton, L. L. Hand, A. Alden, C. Warren, and N. Newcombe, "The Malleability of Spatial Skills: A Meta-Analysis of Training Studies," Psychological Bulletin, 139(2), 352–402, 2013.