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Efficacy of Various Spatial Visualization Implementation Approaches in a First-Year Engineering Projects Course

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Introduction

Spatial visualization (SV) skills are both learnable[1] and highly correlated with success in engineering. Convinced that improvement in our engineering students' spatial visualization skills would support improved retention in the College of Engineering and Applied Science at the University of Colorado Boulder—a highly research-active university, the first-year engineering projects course faculty team embarked on an evolving and escalating effort to cultivate students' spatial visualization (SV) abilities. Starting in the 2013 academic year, the SV skills of cohorts of entry-level engineering students were measured before and after their completion of a first-year engineering project design course. Students were assessed using the *Purdue Spatial Visualization Test: Visualization of Rotations*[2] (PVST:R) pre- and post-tests. In subsequent semesters of the same course, each student cohort was assessed before and after a specific SV implementation approach to see the impact of the addition of various formal curricular approaches to cultivate spatial visualization skills.

Our motivation to implement and study spatial visualization skills came primarily from the evidence in the literature concerning historic gender differences in SV ability and the effects of SV skills on retention in engineering. For decades, studies using the PVST:R and other spatial visualization tests have consistently shown gender differences[3,4] in which male students significantly outperform female students. The source of this gender gap is under investigation; Yoon et al. recently confirmed that the PVST:R does not contain a test bias against gender[5]. Additionally, Sorby and Baartman performed a six-year longitudinal study that showed that a first-year SV intervention increased retention rates in engineering[6].

Without a clear understanding of the source of the SV gender gap, but convinced that ample evidence existed to support SV intervention as a powerful retention tool with the potential to differentially impact female students, we began to incorporate SV skill-building curriculum into the college's *GEEN 1400: First-Year Engineering Projects* course. Over time, our results motivated us in an escalating fashion to intervene *more* with SV curriculum. This paper describes the various spatial visualization approaches and implementations across five semesters, and reports the resulting efficacy (or lack thereof) of each method.

Methods

To augment the first-year design experience of entry-level engineering students, varying approaches to the addition of formal spatial visualization curricula were implemented and tested during five semesters. We admittedly "failed often in order to succeed sooner" and iterated our implementation approach after each semester's SV growth results were assessed.

The PVST:R was consistently administered at the beginning and end of each implementation for those students who did not originally pass. Our implementation approaches to improve students' SV skills included:

- *Intervention 0*: No special training in SV outside of regular design coursework (that is, hope for the best); pre- and post-test data available as baseline
- *Intervention 1*: In-course SV curriculum and homework assignments, with the potential to earn extra credit
- *Intervention 2*: Voluntary out-of-class SV workshops with homework assignments
- *Intervention 3*: A mandatory out-of-class, four-part SV workshop series for students who did not initially "pass" the SV assessment.

Table 1. Details of the various spatial visualization implementation approaches employed.

Intervention Method & Semester	Institutional Investment			Student Accountability	Student Incentive	Curriculum Framework
	People	Places	Things			
0 Spring 2013	None	None	None	None	None	None
1 Fall 2013	Existing design course faculty (nine faculty members)	None beyond existing class	In-class SV lecture, online homework assignments	5 graded homework assignments	Extra credit awarded if >5 homework assignments completed	Computer-based online practice sets
2 Spring 2014	Graduate student TA (paid hourly)	Dedicated classroom for 6 hours weekly	In-class SV lecture and online homework assignments	Voluntary attendance at out-of-class SV workshops	Beverage gift cards and prize lottery available to students who attended SV workshops	Hands-on workshops and computer-based online practice sets
3 Fall 2014 and Spring 2015	Dedicated faculty member and undergrad TA (paid hourly)	Dedicated classroom for 6 hours weekly	In-class SV lecture, hands-on workshop material (workbooks, blocks, play dough, etc.)	Required attendance at workshops for students who did not pass SV assessment	5% of semester course grade when SV assessment target met	In-person, hands-on curriculum for 4 out-of-class SV workshops

A comparison of various lenses concerning the implementation approach is provided in Table 1. The *institutional investment* lens refers to the resources committed to the SV implementation, including faculty/student employees (*people)*, the classroom time/space (*places)*, and classroom resources (*things)*. The *student accountability* lens details the method used by the faculty to encourage and quantify the student participation. The *student incentive* lens refers to the mechanisms used to motivate students to practice and build their SV skills. Lastly, the *curriculum framework* lens describes the method used to implement the SV curriculum.

To begin, in spring 2013, no special training in spatial visualization was provided to students as we explored whether the SV skills of the 205 engineering students who took the PVST:R pre- and post-assessment would be boosted through the design course itself, or through other factors in the first-year engineering curriculum. This implementation approach provided baseline SV data for a typical first-year cohort.

During the subsequent fall 2013 semester, the next cohort of 279 students was introduced to SV concepts in the form of an introductory SV lecture provided by the design course faculty. In addition, students completed five graded, online SV homework assignments—and could complete more for extra credit. All students were required to complete the assignments, regardless of PVST:R score.

The spring 2014 cohort of 305 engineering students was also introduced to SV concepts in an introductory lecture. Students who did not achieve a passing threshold of at least 20 (of a possible 30) on the PVST:R pretest were asked to participate in voluntary, out-of-class SV workshops led by a graduate student teaching assistant (TA). A classroom was dedicated for six hours weekly for the voluntary workshops, and the TA used online homework assignments and hands-on curriculum to teach SV skills. To incent student participation, a "coffee cart" beverage gift card (~$5 value, good for any beverage available) was provided each week to student workshop attendees, and attendees who ultimately achieved a score of $\geq$20 on the SV assessment were entered into a lottery to win an iPad.

Finally, during the fall 2014 semester a cohort of 342 students participated in four, two-hour, out-of-class SV workshops, which were *required* for all students who did not achieve scores of at least 20 on the PVST:R pre-test. A dedicated faculty member, assisted by an undergraduate TA, held weekly out-of-class workshops for two four-week sequences. The two sessions gave students who did not achieve success with the first session the opportunity to repeat the SV workshop series. This approach provided much higher commitment levels to both student participation and passing the SV assessment, and put minimal burden on the course instructors. The SV workshops were presented in "Montessori style" with the classroom set up in stations through which students rotated during the two-hour workshop. The stations made use of hands-on materials including workbooks, blocks, play dough, pen and paper sketching, etc. For the first time, participation in the SV workshops was mandatory for non-passers, and they earned 5% of their semester grades once they passed the PVST:R test. The assessment was administered two additional times—after four weeks of workshops and again after eight weeks.

Given the strength of the fall 2014 outcomes shown in Table 2, a similar strategy for delivering the SV curriculum was implemented for the spring 2015 cohort of 316 students in two design-focused first-year engineering projects courses. The SV workshops were scaled from just over 53 students to 67, with the workshops once again being completed during the first half of the semester to give students the opportunity to apply their newly acquired SV skills to their design projects.

As seen in Table 1, the implementation approach escalated each semester across all lenses. The results are presented in Table 2 and discussed below.

Findings

Table 2. Pre- and post-test results from various implementations.

Intervention Method & Semester	# Students in Cohort	Pre-Test Passing Rate (%) (*# of students*)	Average Pre-Test Score of Workshoppers*	Average Post-Test Score of Workshoppers	Workshoppers Post-Test Passing Rate (%) (#)
0 Spring 2013	**205**	**78% (160)**	**15.8**	**17.3**	**29% (13)**
Men	160	81% (130)	16.2	18.0	33% (10)
Women	45	67% (30)	15.1	16.1	20% (3)
1 Fall 2013	**279**	**65% (180)**	**15.6**	**18.0**	**37% (37)**
Men	189	72% (137)	15.6	17.6	38% (20)
Women	90	48% (43)	15.7	18.5	36% (17)
2 Spring 2014	**305**	**84% (256)**	**16.2**	**22.2**	**41% (20)**
Men	217	91% (197)	16.6	21.6	30% (6)
Women	88	67% (59)	16.0	22.8	48% (14)
3 Fall 2014	**342**	**85% (289)**	**15.4**	**23.6**	**94% (50)**
Men	263	92% (242)	16.0	23.9	95% (20)
Women	79	59% (47)	15.0	23.5	94% (30)
3 (cont.) Spring 2015	**316**	**79% (249)**	**15.3**	**21.6**	**82% (55)**
Men	231	84% (194)	15.3	21.6	84% (31)
Women	85	65% (55)	15.4	22.0	80% (24)

**To clarify, students who initially did not pass are referred to as "Workshoppers"*

Even though cohort 0 of entry-level students was immersed in an academic engineering culture and the first-year engineering projects-based design course included a significant amount of drawing and visualization of three-dimensional designs, without an SV curricular intervention, only 29% of students who initially did not pass the pre-test increased their SV skills to pass the post-test by semester end. We were not satisfied with that outcome.

Intervention 1, in which all students (including those who initially passed the SV pre-test) completed online, computer-based practice sets as homework, saw only 37% of initial non-passers ultimately passing the post-test. Again, we were not satisfied with this outcome.

In Intervention 2, only the 49 students with scores below 20 (the "pass" threshold) were asked to participate in voluntary, out-of-class spatial visualization workshops led by a graduate teaching assistant. Employing a "voluntary, this is good for you" approach did not work: of the 49 students, 32 (65%) completed one or more of the homework assignments, and only 26 (53%) took the workshop post-test—with a disappointing 41% ultimately passing the post-test threshold.

While both Interventions 1 and 2 pre- to post-test PVST:R scores showed statistically significant improvement, the SV skill gains and participation rates fell far short of the course learning outcome goals. Still believing that improved spatial visualization skills would lead to improved retention in the engineering program, a much more intensive *and intentional* implementation of the SV curriculum was designed for fall 2014 and spring 2015 (Intervention 3). Our goal became clearer: to aggressively develop SV skills among *all* ~600 students enrolled annually in the first-year engineering projects course. To achieve this outcome, we knew we needed a higher-stakes implementation approach, to which we dedicated more resources.

Thus, Intervention 3 required the most institutional investment in people, places and things—accompanied by much higher student accountability and incentives. As seen in Table 2, students achieved by far the best SV skill development gains. Ultimately, 94% and 81% of initial "non-passers" achieved the threshold of 20 by course end in fall 2014 and spring 2015 respectively, with a full 99% and 96% of the fall and spring cohorts in the first-year design course ultimately achieving the SV threshold of 20. Finally, we were satisfied that our model met our aggressive SV improvement goal—and hopefully these results are impactful enough to realize long-term benefits in retention and engineering success.

Gender Does Matter. Across all interventions and cohorts we found significant gender differences among the students with pre-test scores of less than 20. With Intervention 3, the SV performance gap between male and female students was closed during both the fall and spring semesters. With the Intervention 3 fall 2014 cohort, 60% of initial non-passers were women, even though only 23% of the students in the course were female. The passing rate for male and female students began at 92% and 59% respectively during fall 2014; this was a statistically significant difference in the passing rate ($p < 0.05$). The post-intervention passing rate was 99% and 98% for male and female students respectively—no longer statistically different ($p>0.05$). For the spring 2015 cohort, the passing rate for male and female students was again statistically significantly different at 85% for males and 65% for females. The post-intervention passing rate was 98% and 94% for male and female students respectively, again no longer statistically different due to gender ($p>0.05$).

Resource investment matters. We have found that *doing our best* with SV skill development requires institutional investment of about one course equivalent of faculty time spread throughout the year, accompanied by one undergraduate TA for every 50 students receiving the SV intervention. With this model, we believe we can impact about 250 engineering students annually. And, with approximately 20% of our incoming first-year engineering students needing SV skill building, we expect to be able to implement this out-of-class workshop model to an entering cohort of up to 1,250 students.

Further, our results show that both student and faculty accountability affect the outcomes. We employ a faculty matrix accountability model designed to require little time for, but lots of caring from, the course instructors. The instructors of the individual sections of the design course are continuously kept abreast of their students' progress by the dedicated SV faculty member. Typically, four or five students in each section (of ~30) need the SV intervention. Accountability for students to participate in the workshops (and receive the 5% of their course grades) lies with the course instructors, not the SV instructor. Thus, communication and mutual agreement on accountability are necessary for achieving student success.

As we learn more about what materials help our students most effectively, we anticipate a refinement of the course materials and activities (see details in the Appendix). A post-workshop survey found that time spent with the TA, drawing, and the hands-on blocks were the most beneficial materials. The least beneficial materials included the online computer tutorials and quizzes. We will pursue more creative activities for each of the stations; for example, we have planned an inductive learning station that asks students to describe orthographic views of objects while blindfolded. As always, we plan to *fail often to succeed sooner* and continue to improve upon the lessons learned from the previous interventions.

Appendix

Details about the activities used during the various interventions: Generally, successful activities involved physical implementation of the SV curriculum, while unsuccessful activities involved virtual (computer) interfaces.

- Online homework assignments (*unsuccessful*, used in Interventions 1 and 2)—Students were assigned practice sets via the class website. Practice sets involved selecting the correct multiple choice answers without requiring students to show work and/or explain their responses. Then, correct answers were provided by the website.
- Block and Draw (*successful*, used in Intervention 3)—Students used square blocks to build objects. Next, they used pencil on isometric graph paper to draw the isometric view of the object. Then they traded objects with another student, and drew the other object.
- Workbook Sessions (*successful*, used in Intervention 3)—Students use a workbook[1] to practice applying various curricular topics like drawing orthographic views or defining the 2-axis rotation. Students were required to show their work, select multiple choice answers, and check their answers in the solutions manual. The SV faculty and/or TA discussed any troublesome problems and provided strategies for each curricular topic.

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