Analysis of Multi-Modal Spatial Visualization Workshop Intervention across Gender, Nationality, and Other Engineering Student Demographics

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***Abstract*—Spatial visualization (SV) skills are both learnable and linked to student success in engineering. Our work was motivated by previous research revealing a gender gap in SV skills that favors male engineering students. A multi-modal SV workshop intervention was incorporated into a first-year engineering projects course with the goal of fostering SV skills for all students. An analysis of SV skills, as measured by the Purdue Spatial Visualization Test (PSVT), preceding and following workshop participation is presented. SV workshop results were studied for five undergraduate engineering student demographic subsets: 1) gender, 2) first-generation status, 3) nationality, 4) socioeconomic status, and 5) underrepresented minority status. Both female and international students were found to arrive at engineering college with less-developed SV skills. Since both populations are rapidly growing in the nation's engineering colleges, closing the SV performance gap is compelling. The multi-modal SV workshop provided substantial support to all students, with a median 23% performance gain. And, workshop attendees improved their PSVT passing rate (achieving a 20-point threshold) from 0% to 92%. Results demonstrate that this replicable multi-modal SV workshop can close SV skills performance gaps among all engineering students.**

Keywords—student retention; gender gap; hands-on; spatial visualization; first-year engineering

I. INTRODUCTION

Spatial visualization (SV), the ability to mentally manipulate two- and three- dimensional objects, is a foundational skill for students and professions in the science, technology, engineering and math (STEM) fields. Additionally, SV abilities have been linked to student retention in engineering and happily, they are learnable [1].

Previous research revealed a gender gap in SV skills that favors male engineering students [2]; the extent to which other student demographics or characteristics may be tied to differentiated SV abilities is unknown. Between 2004 and 2014, the national growth of undergraduate engineering enrollments for women, international, and underrepresented minority (URM) students was rapid (Table 1) [3]. Engineering colleges have an ethical imperative to facilitate the best possible opportunities for each of their students to succeed and persist in engineering, regardless of student characteristics and demographics—including gender, nationality and others.

In 2014, faculty at the University of Colorado Boulder incorporated SV interventions into several first-year engineering projects courses with the goal of nurturing spatial visualization skills for all students. The faculty were motivated by Dr. Sheryl Sorby's work at Michigan Technological University and by the ENGAGE Engineering initiative which highlighted the ways that SV skills improve performance and retention in engineering. Many intervention designs were previously implemented at CU-Boulder, but with varied and less-than-desired, success [4]. The Purdue Spatial Visualization Test: Visualizations of Rotations (PSVT:R), a cognitive test designed to measure SV ability in 3-D mental rotation, was administered before and after each intervention [5, 6]. Largely unsatisfied with their early results, the faculty developed a required four-week multi-modal SV workshop series for students who did not initially pass the PSVT.

This paper introduces the multi-modal SV workshop and presents an analysis of student SV skills preceding and following workshop participation. SV skill results are explored by 1) gender, 2) first-generation status, 3) nationality, 4) socioeconomic status, and 5) underrepresented minority status in order to quantify the effect of the workshop on SV skills development for a broad range of undergraduate engineering student populations.

TABLE I. NATIONAL UNDERGRADUATE ENGINEERING ENROLLMENTS

	2004 - 2005	*2013 – 2014*	*% Increase*
Female	63,980	117,511	84%
International	18,954	53,368	182%
URM	54,813	92,488	69%

II. RESEARCH QUESTIONS

- Do differential SV skills exist upon entry to the first-year engineering projects class across 1) female and male students; 2) first-generation students and not; 3) international and domestic students; 4) low SES students and not; and 5) URM students and not?

This material was motivated and partially supported by the ENGAGE project.

- To what extent does the multi-modal SV workshop impact both student PSVT performance and passing rate?
- Does the multi-modal SV workshop support *all* populations of engineering students in developing their SV skills?

III. METHODS

A. Research Methods

During the first week in each of four semesters (fall 2014, spring 2015, fall 2015 and spring 2016), 1,521 students enrolled in first-year, hands-on, design-based engineering projects classes in the College of Engineering and Applied Science at the University of Colorado Boulder were administered the PSVT. Based on previous research, a score of 20 points or more (out of 30 possible) constituted a passing grade [7]. To promote accountability, a passing grade of $\geq$20 earned full credit for 5% of the 16-week semester course grade. The 251 students (17%) who did not pass the initial PSVT (scores < 20) were required to attend an out-of-class four-week series of spatial visualization workshops; these 251 students are referred to as "*workshoppers"* in this study.

B. Undergraduate Engineering Student Demographic Subsets

Undergraduate engineering students were studied based on five dichotomous demographic subsets, including 1) gender, 2) first-generation college status (first-gen), 3) nationality, 4) low socioeconomic status (low SES), and 5) whether their race or ethnicity is an underrepresented minority (URM) in engineering.

The percentages of each demographic subset in the workshopper population, compared to the engineering college as a whole, are presented in Table II. The percent of workshoppers is cumulative across the 2014-2015 and 2015-2016 academic years; the percent of college enrollment is the average of the 2014 and 2015 first-year students [8]. The difference is provided to indicate the over and/or underrepresentation of each demographic subset among the SV workshops. Results show that both female and international students were greatly overrepresented in the workshops by 72% and 155%, respectively. The overrepresentation of these students in the workshop population indicates that they had differentially low PSVT pre-test passing rates, and suggests that these student groups tended to arrive at the engineering college with differentially less-developed SV skills, as measured by the PSVT.

Of note is that URM students were *underrepresented* among the workshoppers. This finding is encouraging, but may be because many rising first-year URM students attended a one- or two-week summer bridge program on campus the summer before their first year of engineering college, during which all students took the SV test and participated in a shorter version of the SV workshop. Also contributing to the low number of URM workshoppers may be that the SV intervention was also done for students in a first-year design course in a pre-engineering program that has a lower representation of URM students than is found for the engineering college overall.

TABLE II. WORKSHOPPER ENROLLMENT COMPARED TO ENGINEERING COLLEGE ENROLLMENT

	Percent of SV Workshoppers	***Percent of Engineering College***	***Percent Difference***
Female	50%	29%	+72%
First-Generation	16%	15%	+7%
International	23%	9%	+155%
Low SES	20%	17.5%	+14%
URM	13%	16%	-19%

C. The Multi-Modal Spatial Visualization Workshop

The multi-modal SV workshop was designed to loosely mimic a Montessori learning approach, allowing students to explore and learn materials by self-paced discovery as opposed to direct instruction, providing a range of activities that students encounter in each two-hour workshop, and designing materials so that a range of senses are called into action during each session.

The SV workshop was organized into two, four-week sessions. As an example, the first session focused on four foundational SV skills: 1) isometric views, 2) orthographic drawing, 3) 1-axis rotations, and 4) 2-axis rotations. The second session addressed more specific challenges, such as inclined planes, curved surfaces and timed problem solving.

Each two-hour workshop began with a brief topical introduction (e.g., isometric views, orthographic drawings, 1-axis and 2-axis rotations, etc.), after which students rotated through four stations that featured different activities on the same topic. For example, the "Block and Draw" station required students to build an object (tactile sensation) and then draw the object from various isometric viewpoints (physical task). In comparison, the "Peer Teach" station challenged students to watch a peer build an object (visual sensation) and then describe to/teach him/her how to draw the isometric view of the object (verbal task). The multi-modal nature of the SV workshop series thus created opportunities for students to practice each SV skill by tapping into a variety of sensory pathways [9].

The SV workshop was offered in the early evening twice weekly for a four-week session; a makeup workshop was also offered each Sunday afternoon. Thus, a student had three different opportunities to attend each week's two-hour workshop. Students were required to attend all four weeks of the session in order to retake the PSVT, which they were required to pass to earn 5% of their design course grade.

A second four-week session, with the same design but different content, was provided for students who did not pass the PSVT following the first session of workshops. This eight-week progression was offered during the first half of the semester in order to facilitate students in cultivating their SV skills before their course workloads heightened, and was designed so that students could immediately apply their newly developed SV skills that same semester in their design courses.

A single faculty member taught the eight weeks of workshops, managed the SV workshop across the multiple sections of three first-year project classes, and maintained communication with both the first-year project faculty team and students involved in the workshops. The SV workshop was considered a half teaching credit each semester for the faculty member (thus equivalent to one course over the entire academic year).

D. Spatial Visualization Skill Metrics

The effects of the multi-modal SV workshop were quantified by comparing three pre- and post- workshop metrics: 1) the percentage of students who scored equal to or greater than 20 points (passing rate, PR), 2) the median integer score out of 30 possible points (performance, PF), and 3) the median integer difference between the post-test and pre-test scores for workshoppers (gain, G). Each of the 1,521 first-year projects class students took a pre-test; only the 251 workshoppers took the post-test. For non-workshoppers, the pre-test score and post-test scores were made equal for statistical analysis. The median PF scores were reported instead of the mean scores since the PF score is an ordinal variable.

E. Statistical Analyses and Software

Fisher's Exact Tests (a two-sample exact test for proportions) were used to test for statistically significant differences between passing rates. Mann-Whitney U tests (a nonparametric test analogous to the t-test for continuous data) were used to detect statistically significant differences in the ordinal performance metric. In each case, statistical significance was determined using an $\alpha = 0.05$. Statistical analyses were performed using MATLAB (MathWorks, Inc., Natick, MA). Effect sizes were not reported since the statistical analyses were studying the entire population and not making inferences based on a sample population.

IV. FINDINGS

PSVT pre-test and post-test results for the entire cohort of first-year engineering projects students and workshoppers are presented, by demographic subset, in Tables III and IV, respectively. Shaded cells denote statistically significant differences between the demographically dichotomous groups, and p-values are provided as superscripts.

While the pre-test and post-test performance scores (PF) for the entire cohort ("All") did not change (median scores of 25), the passing rate (PR) for the pre-test and post-test increased from 82.8% to a remarkable 98%. In other words, *nearly all* of the 1,521 first-year students completed their engineering projects class with SV skills that *surpassed the 20-point threshold*.

Looking deeper into these results, both the pre-test PF and PR for the female and international student cohorts were of particular interest (Fig. 1). Echoing the findings of other researchers, data from this study also revealed a gap in SV skills with respect to gender. In the pre-test PR metric, female students (PR = 67.5%) passed the test at a considerably lower rate than their male peers (PR = 88.2%). A similar gap was found between international and domestic students, with international students (PR = 61.4%) passing the test at noticeably lower rates than domestic students (PR = 85.2%). International students passed the SV test at the lowest rate compared to each of the other demographic populations, as measured by the PR metric. These results are not only indicative of a gap in SV skills with respect to gender, but also a gap in SV skills with respect to the nationality (international versus domestic) of first-year engineering students at our university. Also, no differences were found among the first generation status, socioeconomic status, nor URM status demographic subsets—which further highlights the differences between female and international students compared to their peers.

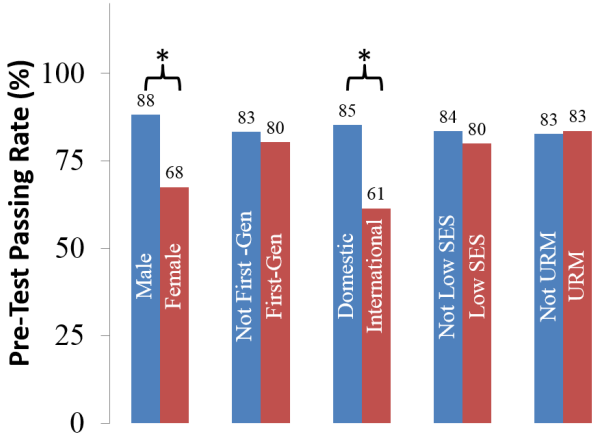

Fig. 1. Entire cohort pre-test passing rate. (n = 1,521). The asterisks indicate statistically significant differences between passing rates ($p < 0.001$).

For the 251 workshoppers (Table IV), the median pre-test PF score was 17, which improved to a median post-test PF score of 23. The improvement of all workshoppers from the pre- to the post-test was statically significant (p's < 0.001) for all demographic groups (Fig. 2).

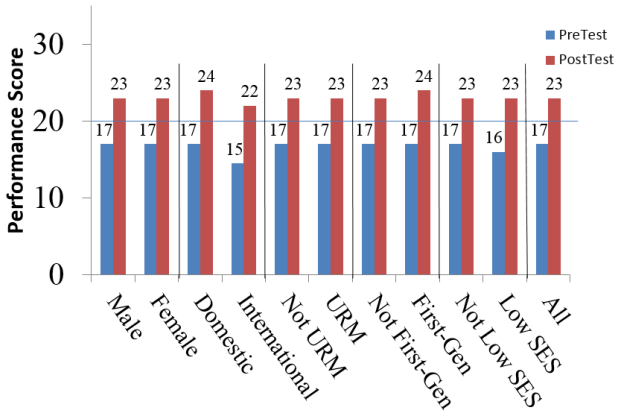

Fig. 2 Workshopper median pre- and post-test performance scores (n = 251). The horizontal line indicates the passing threshold of 20 points. All demographic subsets improved at a statistically significant level (p's < 0.001).

The pre-test PR, by definition, was 0% for workshoppers and improved to a 91.6% PR. Nearly all students who completed the workshop series improved their SV skills and surpassed the standard threshold of 20. And, the median PSVT gain was 7 points (23% increase) for all workshoppers.

These findings demonstrate that the multi-modal SV workshop was successful in improving student SV skills for students from all demographic subsets, thus achieving our overarching goal of *equity in access* to an engineering education.

Of note, only the international workshoppers started and ended the workshop with significantly lower skills than the alternative category, their domestic peers. However, the median international *and* domestic student gains were equivalent (7 points), indicating that both benefited comparably from the workshop.

No statistically significant differences were detected by gender, first-generation status, low SES status, or URM status for the workshoppers; for each of these demographic groups, students scored similarly on the pre-test and improved similarly on the post-test.

TABLE III. ENTIRE COHORT PRE-TEST AND POST-TEST PERFORMANCE AND PASSING RATES

Characteristic	*Category*	*Student Count*	*Median Pre-Test PF (points)*	*Pre-Test PF Interquartile Range (points)*	*Pre-Test Passing Rate (%)*	*Median Post-Test PF (points)*	*Post-Test PF Interquartile Range (points)*	*Post-Test Passing Rate (%)*
Gender	Male	1127	26	6	88.2	26	5	98.6
	Female	394	22 $^{.000}$	6	67.5 $^{.000}$	24 $^{.000}$	4	96.2 $^{.005}$
First-Gen	No	1287	25	6	83.3	25	5	98.3
	Yes	234	24 $^{.035}$	6	80.3 $^{.300}$	25 $^{.021}$	5	96.1 $^{.043}$
International	No	1368	25	6	85.2	25	5	98.6
	Yes	153	22 $^{.000}$	9	61.4 $^{.000}$	23 $^{.000}$	6	92.2 $^{.000}$
Low SES	No	1253	25	6	83.5	25	5	98.3
	Yes	268	24.5 $^{.165}$	6.25	79.9 $^{.154}$	25 $^{.284}$	5	96.3 $^{.052}$
URM	No	1289	25	6	82.7	25	5	98.1
	Yes	232	25 $^{.803}$	6	83.6 $^{.777}$	25 $^{.433}$	4	97.0 $^{.307}$
All		1521	25	6	82.8	25	5	98.0

Shaded cells denote statistically significant differences between the demographically dichotomous groups, and p-values are provided as superscripts.

TABLE IV. WORKSHOPPER PRE-TEST AND POST-TEST PERFORMANCE AND PASSING RATES

Characteristic	*Category*	*Student Count*	*Median Pre-Test PF (points)*	*Pre-Test PF Interquartile Range (points)*	*Pre-Test Passing Rate (%)*	*Median Post-Test PF (points)*	*Post-Test PF Interquartile Range (points)*	*Post-Test Passing Rate (%)*	*Median Gain (points)*	*Gain Interquartile Range (points)*
Gender	Male	125	17	4	0	23	4	93.6	7	4
	Female	126	17 $^{.779}$	5	0	23 $^{.802}$	5	89.7 $^{.362}$	7 $^{.570}$	6
First-Gen	No	210	17	4	0	23	5	91.9	7	4.5
	Yes	41	17 $^{.253}$	5	0	24 $^{.934}$	4	90.2 $^{.758}$	7 $^{.708}$	4
International	No	193	17	4	0	24	4	94.8	7	5
	Yes	58	14.5 $^{.002}$	5	0	22 $^{.001}$	4	81.0 $^{.002}$	7 $^{.818}$	3
Low SES	No	202	17	4	0	23	5	92.1	7	4.5
	Yes	49	16 $^{.614}$	4.5	0	23 $^{.604}$	4.25	89.8 $^{.572}$	8 $^{.953}$	5.75
URM	No	218	17	4	0	23	4	91.3	7	5
	Yes	33	17 $^{.205}$	4	0	23 $^{.821}$	4.25	93.9 $^{.999}$	7 $^{.353}$	5.25
All		251	17	4	0	23	4	91.6	7	5

Shaded cells denote statistically significant differences between the demographically dichotomous groups, and p-values are provided as superscripts.

V. FINAL THOUGHTS

This investigation analyzed the impact of CU-Boulder's multi-modal spatial visualization workshop on first-year engineering students' SV skills (as measured by the PSVT) across gender, nationality and other demographics for four semesters. The workshop resulted in comparable gains to all demographic subsets of students (median gain of 7 points) and SV workshop attendees improved their PSVT passing rate from 0% to 92% (based on a 20-point threshold).

Significant differences existed in the incoming spatial visualization skills of the studied first-year engineering students with respect to gender and nationality, with women and international students initially demonstrating less-developed SV skills (as measured by lower PSVT pre-test performance and passing rates). While the SV skills gender gap is well-established, in this work we also found a similar gap in SV skills between domestic and international engineering students.

Also of significance, this work found a replicable pathway for students to learn the SV skills necessary for student success by attending an eight-hour, out of class SV workshop series. The workshop design engaged one engineering faculty member to support many sections of three first-year engineering design courses, both negating the need for curriculum change within the design courses and for each faculty member to learn to teach SV skill development themselves.

Moving forward, we will assess the longitudinal effects of this multi-modal SV intervention as the students matriculate through the engineering college. We are primarily curious about whether correlations exist between SV scores and success and/or persistence in engineering.

Additionally, we hope to derive an optimal passing threshold for the PSVT based on empirical evidence. Although we have been using a 20-point passing threshold, workshoppers achieved a post-test median score of 23, which implies that students who originally scored 20, 21 or 22 points may have also benefitted from such a workshop. With student success as our primary goal, we question whether we are inadvertently leaving students behind when applying a 20 point threshold.

We found that this replicable, multi-modal SV workshop intervention can benefit each of the studied demographic subsets of students and is particularly important for two fast-growing populations of undergraduate engineering students: women and international students. This finding is of particular importance as universities recruit and admit an increasing number of female and international students to colleges of engineering. In order to promote equity in student success, similar multi-modal SV workshops can be used to develop SV skills and help level the playing field for all students as they matriculate through their engineering degrees. At CU-Boulder, we will continue to develop the SV skills of our students to ensure equity in student success across gender, nationality and all other demographics.

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