Investigation of Spatial Visualization Skills Across World Regions

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***Abstract*—Spatial visualization (SV) skills contribute to success in engineering. However, ample research from American university settings indicates that various subsets of engineering students have significantly less-developed SV skills than those demonstrated by the majority male population. A multi-modal SV workshop intervention was provided within a first-year engineering projects design course in order to "close the SV gap" for all students. A nationality gap was identified in which international students scored dramatically lower on the Purdue Spatial Visualization Test (PSVT) compared to their domestic counterparts. In this paper, an analysis of SV skills segmented by world region is presented. No difference was found between East Asian and domestic students; however, Middle Eastern students scored dramatically lower on the pre-test than East Asian and domestic students across both a performance score (19 out of 30) and passing rate (46%). The Middle Eastern students improved significantly due to the workshop, with median SV gains of 4 points on the performance score and 38% on the passing rate. These results identify first-year Middle Eastern students as being potentially at risk within colleges of engineering due to less developed spatial visualization skills that can be strengthened through targeted, short-duration training and skill development interventions.**

Keywords—student retention; international students; hands-on; spatial visualization; first-year engineering; Middle Eastern region

I. Introduction

Spatial visualization (SV) skills are integral to engineering education, and improve retention in engineering programs [1]. Faculty at a highly research-active university developed a multi-modal SV workshop for students in several first-year engineering projects design courses to improve SV skills.

Previously, we analyzed and disaggregated SV results by various student demographics, including gender, socio-economic status, underrepresented minority status, first-generation college status and nationality [2]. Results replicated the well-established SV skill gender gap, and exposed a surprising result: international students arrived at our engineering college with far less-developed SV skills than their domestic peers. This finding presents an equity issue for universities recruiting an increasing number of international engineering students. Nationally, the undergraduate engineering enrollments for international students increased by 182% between the 2004-2005 and 2013-2014 academic years [3]. Educators have an ethical responsibility to promote equity in student success to an engineering education; our SV research findings identify a student population whose SV skills need significant and early bolstering to scaffold them for subsequent success in their engineering educations.

Other researchers have studied the differences in SV skills among international and domestic (US) students in various forms. Dr. Sheryl Sorby investigated the differences among domestic and international engineering students over many years (1996-2011) with a small population of international students (242 out of 11,441 total) enrolled at Michigan Technological University [4]. This study showed a statistically significant difference in Purdue Spatial Visualization Test (PSVT) scores among Middle Eastern, African, Chinese and Indian students compared to their domestic peers, while students from Far East Asia, South America and Canada showed no differences in SV performance. In addition, Sorby studied students from the United Arab Emirates and compared their PSVT scores to a domestic student population [5]; this work confirmed a gap between the spatial skills of the UAE students compared to domestic students. We were motivated by these findings to ascertain if our international engineering students performed differently on the PSVT than their domestic peers, whether students from various world regions demonstrated differential SV skills, and whether our multi-modal SV workshop intervention could improve student performance on the PSVT. This paper reviews the multi-modal SV workshop intervention and analyzes the pre- and post-test results for students across various world regions.

II. Research Questions

- Do differential SV skills exist upon entry to the first-year engineering projects design class across the following world regions of origin: 1) Americas (except domestic students); 2) Europe; 3) Africa; 4) Middle East; 5) South and East Asia; and 6) Australia and Pacific?
- To what extent does the multi-modal SV workshop differentially impact both student PSVT performance and passing rate for international students?
- Does the multi-modal SV workshop equitably support *all* international students in developing their SV skills?

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III. METHODS

A. Research Methods

Students completed the Purdue Spatial Visualization Test (PSVT) during the first week of class for their first-year, hands-on, design-based engineering projects classes at a highly active-research public university. A total of 2,441 students enrolled in these courses over six semesters (Fall 2014 – Spring 2017). Students who scored above or equal to 20 points (out of 30 possible) passed the test according to a previously used passing threshold [6]. Students who did not initially pass the PSVT (n = 388 or 16% of all students) were required to attend the out-of-class spatial visualization workshop series; in this study, we refer to these students as "*workshoppers.*" Students earned 5% of their semester course grades for passing the PSVT test, which encouraged consistent SV workshop attendance and motivation to perform.

B. World Region Subsets

In the present study, we analyzed our international undergraduate student cohort by world region, using the world regions defined by the World Bank [7]. We identified six world regions from which our international students were citizens: 1) Americas (except domestic students); 2) Europe; 3) Africa; 4) Middle East; 5) South and East Asia; and 6) Australia and Pacific. Among the six world regions, only the Middle East and Asian regions had large enough student populations in our six-semester dataset to analyze statistically. We considered domestic students (USA nationals) a seventh world region for comparison. 236 international students (10% of all students) enrolled in the course and 84 international students participated in the SV workshops (22% of workshoppers). Table II depicts the workshopper enrollment across world regions.

Note that Middle Eastern students are over-represented as workshoppers (14%) compared to their enrollment in the course overall (4%) while domestic students are underrepresented (78% of workshoppers versus 91% of the course).

TABLE I. WORKSHOPPER ENROLLMENT ACROSS WORLD REGIONS

	Number of Students	Percentage of Students in Course	Percentage of SV Workshoppers
Americas	12	< 1%	< 1%
Europe	8	< 1%	< 1%
Africa	2	< 1%	< 1%
Middle East	102	**4%**	**14%**
South and East Asia	111	5%	6 %
Australia and Pacific	1	< 1 %	0%
USA (Domestic)	2,205	**91%**	**78%**

C. The Multi-Modal Spatial Visualization Workshop

Workshoppers attended a four-week evening SV workshop during which they rotated through various hands-on activities in two-hour sessions to study SV topics such as isometric drawing, orthographic views, etc. The PSVT was re-administered following workshop completion. If students did not pass the PSVT on the second attempt, they were required to participate in an additional four-week workshop series before being eligible to retake the PSVT a final time. This form of the SV intervention was administered over six semesters to more than 2,400 engineering students. Additional detail concerning prior SV interventions and results are available in a previous paper [8].

D. Spatial Visualization Skill Metrics

The effects of the SV workshop were quantified by comparing two pre- and post-test metrics: 1) the median integer score out of 30 possible points (performance, PF) and 2) the percentage of students who scored equal to or greater than 20 points (passing rate, PR). All students enrolled in the course completed a pre-test while only *workshoppers* completed a post-test. For non-workshoppers, the pre- and post-test scores were made equal for statistical analysis. Median (rather than mean) PF scores are reported 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 $\alpha = 0.05$. Statistical analyses were performed using MATLAB (MathWorks, Inc., Natick, MA). Effect sizes were not reported since the statistical analyses studied the entire population instead of making inferences based on a sample population.

IV. FINDINGS

Table II presents the number of students from each world region (in total and by gender) as well as the performance score (PF), passing rates (PR), and interquartile ranges for the pre- and post-test. Only the Middle East, East Asia, and domestic world regions were studied in depth due to the limited number of enrolled engineering students from all other world regions. The number of students from the Middle East and East Asia regions were similar (n = 102 and n=111, respectively) while the number of domestic students was an order of magnitude greater (n = 2,205).

Figures 1 and 2 depict the median PF and PR for the pre- and post-test across world regions. The Middle Eastern student pre-test PF and PR scores (19 points and 46%, respectively) were significantly lower than both the East Asian and domestic student scores. After the workshop series, the Middle Eastern student post-test PR and PF scores improved dramatically (to 23 points and 84%), but were still significantly lower than the post-test scores for both East Asian and domestic student populations. However, no difference was found between the East Asian and domestic students across both metrics for the pre- and post-test. In fact, East Asian and domestic students achieved the identical median pre- and post-test PR scores (25 and 26, respectively, out of 30).

TABLE II. 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 (%)
Middle East	Total	102	19	10	46	23	5	84
	Male	79	20	10	52	23	5	91
	Female	23	14	10	26	22	5	61
South and East Asia	Total	111	25	8	79	26	6	98
	Male	84	26	7	83	26	6	99
	Female	27	21	7	67	23	6	96
USA (Domestic)	Total	2,205	25	5	86	26	5	98
	Male	1622	26	5	91	26	4	98
	Female	583	23	5	72	24	4	97
All Students	Total	2,441	25	6	84	25	5	98

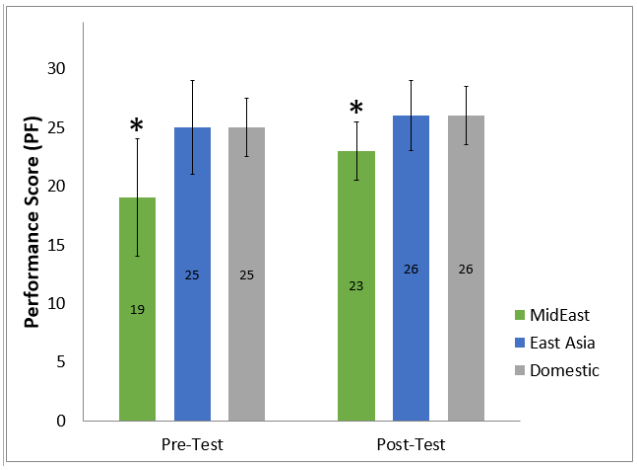

Fig. 1. Median pre- and post-test performance scores for Middle Eastern (MidEast), South and East Asia (East Asia), and domestic students. Error bars display interquartile range. Asterisks indicate statistically significant differences ($p < 0.01$).

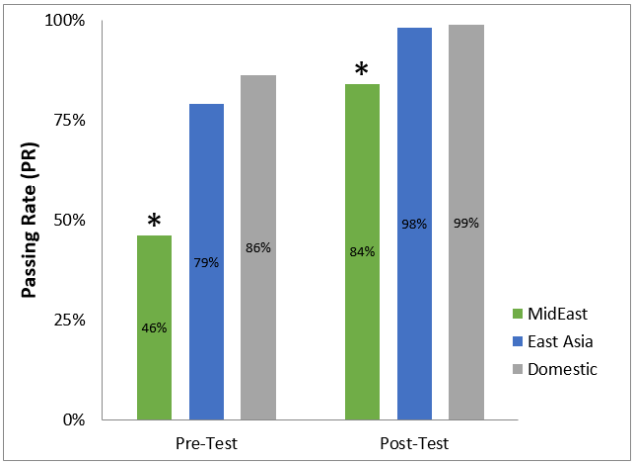

Fig. 2. Passing rates for Middle Eastern (MidEast), South and East Asia (East Asia), and domestic students. Asterisks indicate statistically significant differences ($p < 0.01$).

We studied the results from the Middle Eastern students in more depth by disaggregating the data by gender, as shown in Figures 3 and 4. These results reveal an exaggerated gap in SV skills between Middle Eastern female and male students. Just 26% of Middle Eastern women passed the SV pre-test, compared to 52% of Middle Eastern men (a 26% difference). And, the Middle Eastern women's pre-test PR scores were significantly lower than the pre-test PR scores for Middle Eastern men (14 to 20 points, a 6-point difference). This gender gap among Middle Eastern students is similar in magnitude compared to domestic students (a 3-point difference in PF and a 19% difference in PR). However, domestic women and men scored dramatically higher than their Middle Eastern counterparts on both the PR and PF metrics. In fact, the Middle Eastern women pre-test PF and PR were the lowest across all world regions and gender by a large margin. Across genders, the after-workshop post-test PF and PR scores were largely improved for all Middle Eastern students; male students improved their PF scores by 3 points and their PRs by 39% while female students improved their PF scores by 8 points and their PRs by 35%.

Looking deeper, a stark difference is observed in the post-test PRs between Middle Eastern women and all other students (Table II). All post-test PRs are greater than 90% for all tested student populations, except for Middle Eastern women who passed the PSVT at a rate of 61%. However, the Middle Eastern women are a small cohort of students ($n = 23$), and the PR metric can thereby be deceiving. A 61% post-test PR indicates that 14 Middle Eastern women passed the PSVT while nine women did not achieve a passing rate. The overall passing rate of 98% for the entire student cohort ($n = 2,441$) over six semesters likewise shows that only 49 students across the six semesters of workshop never passed the PSVT. To our dismay, Middle Eastern women make up 18% of all students who never passed the PSVT while they make up less than 1% of our student population. Middle Eastern women perform worse on the PSVT both before and after the workshop series compared to all other demographic and geographic cohorts. The SV instructor observed that, as a cohort, these students worked hard on their SV skill development during the workshops; their lower success rates did not appear to be associated with lack of motivation or commitment. He also observed that these students benefitted

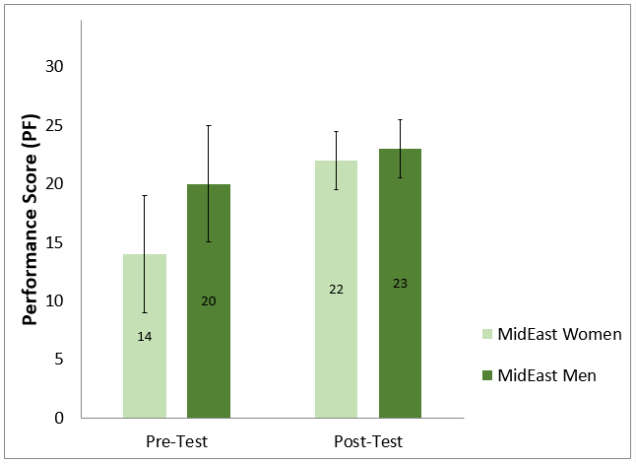

Fig. 3 Performance scores for Middle Eastern (MidEast) women and men for the pre- and post-test. Asterisks indicate statistically significant differences ($p < 0.01$).

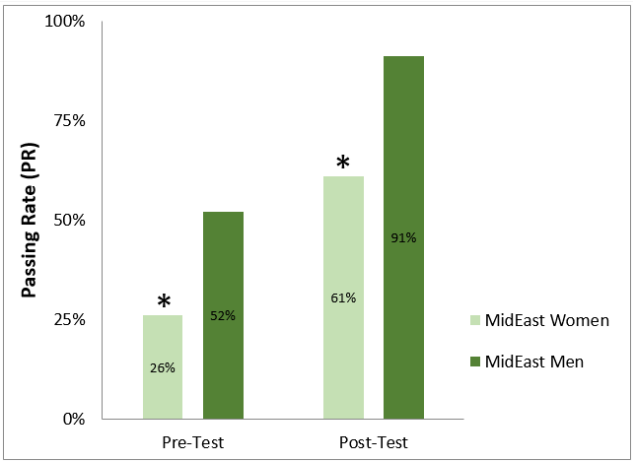

Fig. 4 Passing rates for Middle Eastern (MidEast) women and men for the pre- and post-test. Asterisks indicate statistically significant differences ($p < 0.01$).

from additional practice with skills like 3D sketching, the right-hand-rule, and others.

V. FINAL THOUGHTS

This study examined the differences in spatial visualization skills for students across world regions before and after a SV workshop series intervention. The results indicated that 1) Middle Eastern students achieve lower SV scores compared to their East Asian and domestic peers; 2) East Asian and domestic students perform at a statistically equivalent level; and 3) Middle Eastern women score lower than any demographic or geographic subset of the student population. These findings suggest that a concerted effort must be made to ensure equity in student success in engineering, especially for our (growing) Middle Eastern student population. Clearly, the SV workshop intervention is inadequate for this student population. Now that we know of this gap, our challenge is to find alternative approaches to aid this population and promote equity in student success.

Across both the PF and PR metrics, Middle Eastern students entered and left the SV intervention with lower skills compared to their East Asian and domestic peers. Middle Eastern students improved dramatically in their scores (PF of 19 to 23, PR of 46% to 84%) indicating that the SV workshop series was effective, but insufficient. However, as a group, the baseline SV skills of our incoming Middle Eastern engineering students are so far below our East Asian and domestic students that the four- (or eight-) week workshop series was not enough to "close the gap."

Colleges of engineering may inadvertently admit students into programs in which they are already at a disadvantage since SV skills are not assessed or indicated during the admissions process. With the ample research concerning the gender gap in SV skills and now the growing research indicating that specific international student cohorts perform dramatically differently from their domestic counterparts, administrative reform is called for to ensure equity in student success within our colleges of engineering.

Finally, we conducted an exploratory qualitative investigation of Middle Eastern students' experiences with SV skills development. We were curious about their perspectives on SV skills, their educational backgrounds, and any insights into which aspects of the SV intervention were most valuable. We interviewed two undergraduate engineering Middle Eastern students, Karim and Hana (pseudonyms). Karim is a junior civil engineering major who participated in the SV intervention in Spring 2015 (two years prior to the interview); he scored 17 on the PSVT pre-test and 23 on the post-test after a single four-week workshop series. Hana is a first-year architectural engineering major who participated in the SV intervention in Spring 2017 (same semester as the interview); she scored 13 on the PSVT pre-test, 17 after the first series of SV workshops, and a passing 24 after the second series of SV workshops. Both volunteered to participate in an hour-long interview that was approved by the university's Institutional Review Board.

Karim is interested in architecture and discussed how he has always loved skyscrapers. He thought he was good at spatial visualization; however, he did not pass the PSVT on his first attempt. At first, Karim did not remember much about the SV workshops, but throughout the discussion more and more memories emerged. He recalls thinking that "I actually thought I would do good, but I did very bad," and that "[SV] is something that I say is very easy for me, in my mind, to think about it." He also remembers seeing his progress and knowing that he had improved during the workshop. "I'm pretty sure [I improved] because of the workshop because I thought I remember seeing the bottom, how it changed." Karim described further how the SV workshop teaching assistant helped him with a strategy using the X-Y-Z coordinate system to rotate the object in his mind. While Karim did not provide details concerning his educational background in SV, his interview provided confirmation that students notice their improvement in SV skills during their time in the SV workshop series.

Hana provided a more in-depth description of her SV workshop experience likely because she had just finished the workshop series when the interview was conducted. She described how SV was a skill she had not thought about since playing with blocks in elementary school. She thought she would pass the SV test initially since she already had an interest

in architectural engineering, but was saddened when she scored 13 out of 30 on her pre-test. Initially she thought, "Oh, that will be easy, like, this is a children thing," but then she noticed that "I got a really bad headache that I—like, I don't know, I can flip it with my hand but I can't see the final result in my eyes or in my brain." While describing her experience in the SV workshops, Hana explained that "[the instructor] gave us really strict and straightforward rules, what we should look at when we see an object, what should we look [sic] first, and then second, and then third. And, I also learned the… about the components, the X, Y and Z. This is really tremendously helpful." She reflected that "I really see a big and huge change from just the beginning of the class until today." Hana confirmed that her educational background did not include practicing SV skills (at least since elementary school) and that she imagined herself to have strong SV skills when arriving at engineering college. She went on to detail many ways in which she looks at the world differently after practicing these SV skills in the workshop series.

These initial qualitative findings provide ample motivation to continue with our SV intervention and to investigate further—both quantitatively and qualitatively—the source of the dramatic differences in SV skills among our Middle Eastern students, and what can be done to provide equity in access to a US engineering education.

VI. Acknowledgment

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VII. References

[1] S. A. Sorby, "Educational Research in Developing 3-D Spatial Skills for Engineering Students," *Int. J. Sci. Educ.*, vol. 31, no. 3, pp. 459–480, Feb. 2009.

[2] J. L. Segil, J. F. Sullivan, B. A. Myers, D. T. Reamon, and M. H. Forbes, "Analysis of multi-modal spatial visualization workshop intervention across gender, nationality, and other engineering student demographics," in *Frontiers in Education Conference (FIE), 2016 IEEE*, 2016, pp. 1–5.

[3] "College Profiles: American Society for Engineering Education." [Online]. Available: https://www.asee.org/papers-and-publications/publications/college-profiles#The_Profiles_and_Data_Book. [Accessed: 04-Apr-2016].

[4] S. A. Sorby and N. Veurink, "Spatial skills among minority and international engineering students," *age*, vol. 25, p. 1.

[5] S. A. Sorby, S. Cubero, N. Pasha-Zaidi, and H. Karki, "Spatial skills of engineering students in the United Arab Emirates," *QScience Proc.*, vol. 2015, no. 4, p. 32, Jun. 2015.

[6] S. S. Metz *et al.*, "Implementing ENGAGE Strategies to Improve Retention: Focus on Spatial Skills Engineering Schools Discuss Successes and Challenges," in *American Society for Engineering Education*, Vancouver, BC, 2011.

[7] "The World Bank - Countries by Region." [Online]. Available: http://www.worldbank.org/en/country. [Accessed: 04-Apr-2017].

[8] J. Segil, B. Myers, J. Sullivan, and D. Reamon, "Efficacy of Various Spatial Visualization Implementation Approaches in a First-year Engineering Projects Course," presented at the ASEE Conferences, 2015, pp. 26.590.1–26.590.8.