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“Lend a Hand” Project Helps Students: Improved Spatial Visualization Skills Through Engaging in Hands-On 3-D Printed Prosthetics Project During a 9th Grade Engineering Course

Shaunna Smith

Texas State University - San Marcos, shaunna.smith@hawaii.edu

Kimberly Talley

Texas State University - San Marcos, talley@txstate.edu

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Keywords

spatial visualization, Revised PSVT:R, high school engineering education

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Shaunna Smith and Kimberly Talley

Texas State University–San Marcos

Abstract

Research shows that high spatial ability is linked to success and persistence in STEM. Empirical investigations often report a gender gap in favor of male students. The purpose of this research study was to assess changes to 9th grade engineering students’ spatial visualization skills through engagement in a nine-week collaborative 3-D printed prosthetics project embedded within their existing “Beginning Concepts of Engineering” course curriculum. Using concurrent mixed methods, this study examined pre-/post-test scores on the Revised Purdue Spatial Visualization Test: Rotations (Revised PSVT:R) in connection with gender, course grades, and level of involvement in the project. Both male and female students’ spatial visualization skills improved overall through the project. Higher levels of project involvement had a positive correlation with students’ Revised PSVT:R scores, and semester course grades. Female students had lower Revised PSVT:R scores than their male peers before and after the project; however, females experienced statistically significant gains in their post-project Revised PSVT:R scores. The trend of the closing gender gap that is evidenced by the female and male students’ mean scores suggests that a novel collaborative project, which includes hands-on, spatially-rich activities, can help female students catch up on their spatial visualization and mental rotation skills. This impact is increased when students dedicate more time to the project.

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Introduction and Background

Definitions of spatial ability vary; however, many researchers agree with Lohman’s (1996) broad definition that spatial ability is “the ability to generate, retain, retrieve, and transform well-structured visual images” (p. 98). There are sub-categories within this cognitive ability, including (a) *spatial visualization*, which involves mentally moving an object using *mental rotation* and/or *mental transformations*, and (b) *spatial relation/orientation*, which involves mentally moving your viewpoint while the object remains fixed (Sorby, 1999; Tartre, 1990). Many researchers note that spatial ability can be nurtured through training and practice; therefore, it is not a fixed set of skills one can only be born with (Lohman, 1996; Sorby & Baartmans, 2000). High spatial ability is often linked to success in STEM disciplines and is of great interest to researchers (Lohman, 1996; Maeda & Yoon, 2013; Sorby, 2009; Uttal, Meadow, Tipton, Hand, Alden, Warren, & Newcombe, 2013; Wai, Lubinski, & Benbow, 2009). Many researchers have found that targeted training that uses specific curricula to supplement course content can positively impact spatial ability (Maeda & Yoon, 2013; Sorby, 1999/2009,

Sorby & Baartmans, 2000; Uttal, et al., 2013); however, there is little empirical research that examines the impact of novel engagement in spatially rich, hands-on projects situated within an existing course curricula. The purpose of this research study was to assess changes to 9th grade engineering students' spatial visualization skills through engaging in a nine-week 3-D printed prosthetics project that was embedded within their existing "Beginning Concepts of Engineering" course curriculum.

Spatial Visualization (and Mental Rotations)

STEM researchers, and engineering education researchers in particular, have focused a lot of work on the subcategory of spatial visualization and mental rotations, as it is important for a variety of engineering tasks that require a "strong visuoperceptual sense" (Maeda & Yoon, 2013, p. 70), such as technical drawing, working with computer-aided drafting programs, and visual problem-solving. Spatial visualization and mental rotation skills have been shown to be strong predictors of academic success during first-year engineering (FYE) undergraduate programs because the curriculum focuses on those types of tasks (Maeda & Yoon, 2011; Maeda & Yoon, 2013; Sorby, 1999; Sorby & Baartmans, 2000; Uttal, et al., 2013). Likewise, these skills have been identified as strong predictors for creativity and innovation (Lohman, 1996; Wai et al., 2009).

There are many tests that are used to measure spatial visualization and mental rotations; however, Guay's (1976) Purdue Spatial Visualization Test: Rotations (PSVT:R) is most commonly used, followed by Yoon's (2011) more recently revised version (Revised PSVT:R), which corrected figural errors and formatting concerns. The Revised PSVT:R contains 30 items that challenge the respondent to mentally rotate an object in the same direction as visually indicated in the instructions and choose the correct answer from five possible options. Items consist of 13 symmetrical and 17 nonsymmetrical 3-D objects that are drawn in a 2-D isometric format. Respondents are given 25 minutes to complete the test, which is available in a computer- and paper-based format. The Revised PSVT:R is a psychometrically valid instrument as indicated by Maeda, Yoon, Gyenam, and Imbrie's (2013) study with 2,469 first year engineering (FYE) students (Cronbach's alpha of 0.839), and by Yoon (2011), who indicated that the Revised PSVT:R is a valid tool for measuring mental rotations with students as young as 13.

Gender Differences in Spatial Visualization (and Mental Rotations)

Though many researchers state there is a gender gap in spatial abilities, spatial visualization and mental rotation in particular tend to show larger differences among males and females (Sorby, 1999, 2000, 2009; Maeda & Yoon, 2013; Reilly, Neuman, & Andrews, 2017). Researchers commonly

find that males score higher on the PSVT:R and Revised PSVT:R than their female counterparts. For example, Maeda and colleagues' (2013) study with 2,469 first year engineering (FYE) students found an effect size of 0.678 in favor of males. Unfortunately, this disparity spills over into some non-engineering areas as well, including recently reported gender disparities concerning physical science test questions that require mental rotations skills (Ganley, Vasilyeva, & Dulaney, 2014). However, many researchers have shown that targeted spatial visualization intervention (i.e., scaffolded spatial visualization curricula designed by Sorby, Wysocki, and Baartmans in 2003) can positively impact both male and female PSVT:R and Revised PSVT:R scores in an attempt to minimize the gender gap (Onyancha, Derov, & Kinsey, 2009; Sorby, 2009; Sorby & Baartmans, 2000), and can also positively impact retention rates of females in post-secondary engineering programs (Sorby, 1999, 2001, 2009).

The gender discrepancy observed through assessments of spatial visualization and mental rotations are still not fully understood; however, Maeda and Yoon's (2013) meta-analysis summarized the literature to provide five distinguishable factors that researchers claim may contribute to the phenomenon, including: (1) biological differences in brains, genetics, and development; (2) strategic differences in cognitive processing and problem-solving strategies; (3) experiential differences in exposure to spatial activities and tasks; (4) affective differences including level of confidence and common gender beliefs and/or stereotypes; and (5) test administration differences, including time limits and scoring procedures. The meta-analysis noted that unequitable experiences with spatially-rich materials (e.g., building blocks, interactive computer simulations) and inconsistent testing administration procedures (e.g., manipulation of test items, addition of visual aids, changing time limits) were most notably contributing to the perceived gender gap reported in many research studies. Testing administration procedures can be properly standardized through more rigorous attention to procedures; however, Sorby (1999, 2001, 2009) contends that the inequity of experiences with spatially-rich materials is something that occurs long before entering post-secondary education, wherein she recommends researchers examine spatial visualization skill development with K-12 students.

Spatial Visualization (and Mental Rotations) in K-12 Education

Though most studies using the PSVT:R and Revised PSVT:R to explore the development of spatial visualization and mental rotations focus on post-secondary undergraduate engineering education contexts, many researchers see the importance of working with K-12 populations in order to impact these skills prior to post-secondary enrollment. Using PSVT:R as a pre- and post-test, numerous studies

have found an effect size in favor of males: Stumpf and Eliot's (1995) study with 152 middle and high school students found an effect size of .56; Yue's (2002) study with 12 high school students found an effect size of .48; and Ernst and Clark's (2009) study with 572 middle school and high school participants found an effect size of .35. When conducting targeted intervention using Sorby, Wysocki, and Baartmans' (2003) spatial visualization training curriculum with 263 middle school students (141 in control group, 122 in treatment groups) and 193 high school students (75 in control group and 118 in treatment groups), Hungwe, Sorby, Molzon, Charlesworth, and Wang (2014) found that both males and females in treatment groups improved spatial visualization scores on the PSVT:R. Most notable, the effect size in the treatment groups still favored males (.28 with middle school students and .32 with high school students); however, it showed significant reduction in the gender gap.

Regularly occurring course content, such as recurring experiences with hands-on building, constructing 3-D models in CAD software, and sketching techniques, can significantly impact spatial visualization skills (Hungwe, et al., 2014; Sorby 1999, 2000, 2009). In a study focused on examining the differing spatial visualization impacts of common high school course content, Brudigam and Crawford (2012) used an end-of-course spatial visualization assessment with 207 students enrolled in "Pre-AP Geometry" and 57 students enrolled in "Introduction to Engineering Design." They found that students enrolled in the engineering course scored higher than students enrolled in the geometry course, concluding that the engineering curriculum more positively impacted the students' spatial visualization skills. Additional analysis found that the gender gap was wide in the geometry group with a .47 effect size in favor of males, whereas the gap was much smaller in the engineering group with a .22 effect size in favor of males. Further analysis showed a significant difference between the females enrolled in the two courses, showing a .70 effect size in favor of the females enrolled in engineering, which suggested that the females who chose to enroll in the optional engineering course experienced greater impacts than those who were only enrolled in geometry.

Purpose of the Study

The purpose of this research study was to assess changes to 9th grade engineering students' spatial visualization skills through engaging in a nine-week 3-D printed prosthetics project. In addition to the regular nine-week "Beginning Concepts of Engineering" course curricular unit that included daily spatial visualization challenge prompts and standards-based activities related to engineering advances in the medical field, the teacher added the collaborative hands-on 3-D printed prosthetics project (see Procedures for details). The primary hypothesis for this research was

that students' spatial visualization skills would improve and that the gender gap, if any, would close through involvement in the hands-on 3-D printed prosthetics project, as measured by the Revised PSVT:R. More specifically, research questions included:

1. In what ways does engaging in the 3-D printed prosthetics project impact participants' spatial visualization skills (i.e., mental rotation skills measured by Revised PSVT:R)?
 - a. Is there a connection to gender?
 - b. Is there a connection to level of involvement in the project?
 - c. Is there a connection to "Beginning Concepts of Engineering" course grade?

Methodology

This study took place during the fall 2016 semester and used concurrent triangulation mixed methods to cross-validate and corroborate findings (Creswell, 2003), including pre-/post-test Revised PSVT:R and four ethnographic observations conducted on-site by the research team.

Participants

Participants included 85 9th grade students enrolled in the "Beginning Concepts of Engineering" course at a charter school in the southwestern United States. Of these students, 84 took the pre-project Revised PSVT:R and 68 took both the pre- and post-project Revised PSVT:R. The gender, involvement level, and course grade were known for 64 of these students. The school is an accredited, public, nonprofit, tuition-free charter school with a special curricular focus on science and technology applications. The school is an authorized International Baccalaureate (IB) World School for the Middle Years Programme (MYP) and is a candidate school for the IB Diploma Programme and Career-Related Programme. The school serves approximately 500 students, including males and females in grades 6–12. About 55% of students are economically disadvantaged and approximately 70% of students come from families of Hispanic descent. Thirty-one percent of students require English as a Second Language services (ESL) services at the school.

Procedures

The project took place in the second nine-week term of the fall 2016 semester, during the regularly scheduled class meeting session (one hour per day for 45 days, resulting in a total of 45 hours of participation). As part of the regular nine-week "Beginning Concepts of Engineering" course curricular unit, which included daily spatial visualization challenge prompts and standards-based activities related to engineering advances in the medical field, the teacher

added the collaborative hands-on 3-D printed prosthetics project that included:

- working in small groups of 3–5 students,
- accessing open-source files from the e-NABLE “Lend a Hand” website (<http://enablingthefuture.org/upper-limb-prosthetics>),
- resizing the files to fit specifications for local members in need of prosthetic hands,
- 3-D printing the pieces using the classroom 3-D printer (Makerbot Replicator), and
- assembling each hand to ensure functionality and quality control.

A total of 10 3-D printed prosthetic hands were completed, which were then delivered to e-NABLE for distribution to specific community members in need.

The teacher of the course gave parents and students consent and assent forms, which were signed and returned to the teacher prior to the start of the curriculum unit. Students who declined participation in the research study were still able to participate in the 3-D printed prosthetics project unit as part of their regular course curricula; however, their data were not included within the analysis.

Students completed the Revised PSVT:R twice, with the first administration occurring immediately before beginning the 3-D printed prosthetics project unit and the second administration occurring immediately after completion of the nine-week unit. The test was given in a paper-based format and followed Yoon’s (2011) test administration procedures; participants had 25 minutes to complete all 30 original test items with no test item modifications, manipulations, or additional visual aids. The Revised PSVT:R data were coded to include demographic information, including (1) gender, (2) semester course grade, and (3) level of involvement in the project, which was all provided by the teacher after the completion of the project and data collection. The involvement levels were defined as: somewhat involved during class (1 = Somewhat Involved); very involved during class (2 = Very Involved); and very involved during class and chose to work beyond class during after-school times (3 = Very Involved Plus Personal Time). These levels were recorded by the teacher periodically throughout the project and then averaged.

Four ethnographic observations were conducted on-site by the research team at two-week intervals in order to observe the participants’ engagement in the course activities. The research team used ethnographic observational field note techniques outlined by Fetterman (2010). Each ethnographic observation was coded in NVivo qualitative data analysis software for emergent themes related to instances/negotiations of spatial visualization and mental rotation, involvement in class, and general classroom culture (e.g., gender stereotypes, reactions to “Beginning Concepts of Engineering” course content, student interactions).

Analytic Procedure

To select the most appropriate statistical analysis method, the data set was checked for normality by examining skew and kurtosis with the Fisher and Pearson skew statistics and the Fisher coefficient of kurtosis (Pett, 2016). Many of the groupings within the data (gender, level of involvement, and semester grade) showed enough skew that non-parametric tests were used to adequately analyze the research hypotheses. The Revised PSVT:R scores were normal and, as such, parametric paired *t*-tests or two-sample *t*-tests were included for comparisons of Revised PSVT:R scores and gains. Furthermore, a multiple linear regression was used to develop a model to predict post-project revised PSVT:R scores from the other known variables and three interaction variables. The interaction variables were limited to three in number by following the rule of thumb of a 10:1 ratio of cases to variables for this sample size of 64 (Stevens, 2001). Table 1 presents the null and experimental hypothesis groupings and the statistical tests used to investigate them. When examining data that were non-normal, Spearman’s rho and Kendall’s tau were used to test for association and the Mann-Whitney U-test was used to examine differences in means. Spearman’s rho and Kendall’s tau are both useful for examining associations between two variables that are both at least ordinal in nature (such as course grade). When the independent variable was dichotomous (such as gender) and the dependent variable was both at least ordinal (such as level of involvement) and non-normal, a Mann-Whitney U-test was chosen to test for differences in the means of these two independent samples (Pett, 2016). Throughout this analysis, the data were examined for significance at the 95% confidence level ($\alpha = 0.05$). As the experimental hypotheses were written with an expected direction, one-tailed results were used for the analysis, noting that if the observed changes were in the opposite direction that such a change would also result in the retention of the null hypothesis. For all tests, the analyses were conducted with SPSS.

Results

Overall Increase in Revised PSVT:R Scores Post-Project

The primary interest in the results is to see if there is an effect upon the students’ spatial visual skills from participating in this project. Comparing post- to pre-project scores allows the same student group to act as their own control group as changes are measured in these students’ abilities over the semester-long project. However, there was not a separate control group that took the same engineering course without the 3-D printed prosthetics project; as such, this data is only able to measure the combined effect of the

Table 1

Null and experimental hypotheses for analysis of revised PSVT:R scores, student gender, student involvement, and students' course grades.

Hypothesis Pairs	Statistical Test(s)
H ₀ : Project will not affect [all, female, or male] students' Revised PSVT:R scores. H _a : Project will increase [all, female, or male] students' Revised PSVT:R scores.	Paired <i>t</i> -test
H ₀ : Project will not affect Revised PSVT:R scores for students earning an [A, B, C, or D/F]. H _a : Project will increase Revised PSVT:R scores for students earning an [A, B, C, or D/F].	Paired <i>t</i> -test
H ₀ : Post-project Revised PSVT:R scores cannot be predicted with known variables and interaction variables. H _a : Post-project Revised PSVT:R scores can be predicted with known variables and interaction variables	Multiple Linear Regression
H ₀ : There is no association between [all, female, or male] student involvement and Revised PSVT:R gains. H _a : There is a positive association between [all, female, or male] student involvement and Revised PSVT:R gains.	Spearman's rho Kendall's Tau
H ₀ : There is no association between [all, female, or male] student involvement and pre-project Revised PSVT:R scores. H _a : There is a positive association between [all, female, or male] student involvement and pre-project Revised PSVT:R scores.	Spearman's rho Kendall's Tau
H ₀ : There is no association between [all, female, or male] student involvement and post-project Revised PSVT:R scores. H _a : There is a positive association between [all, female, or male] student involvement and post-project Revised PSVT:R scores.	Spearman's rho Kendall's Tau
H ₀ : There is no association between [all, female, or male] student involvement and course grades. H _a : There is a positive association between [all, female, or male] student involvement and course grades.	Spearman's rho Kendall's Tau
H ₀ : There is no association between [all, female, or male] students' course grade and Revised PSVT:R gains. H _a : There is a positive association between [all, female, or male] students' course grade and Revised PSVT:R gains.	Spearman's rho Kendall's Tau
H ₀ : There is no association between [all, female, or male] students' course grade and pre-project Revised PSVT:R scores. H _a : There is a positive association between [all, female, or male] students' course grade and pre-project Revised PSVT:R scores	Spearman's rho Kendall's Tau
H ₀ : There is no association between [all, female, or male] students' course grade and post-project Revised PSVT:R scores. H _a : There is a positive association between [all, female, or male] students' course grade and post-project Revised PSVT:R scores.	Spearman's rho Kendall's Tau
H ₀ : [All, Female, or Male] students' consolidated level of involvement has no effect on Revised PSVT:R gains. H _a : [All, Female, or Male] students who were only somewhat involved will have lower Revised PSVT:R gains than more involved students.	Two-sample <i>t</i> -test
H ₀ : [All, Female, or Male] students' consolidated level of involvement has no effect on pre-project Revised PSVT:R scores. H _a : [All, Female, or Male] students who were only somewhat involved will have lower pre-project Revised PSVT:R scores than more involved students.	Two-sample <i>t</i> -test
H ₀ : [All, Female, or Male] students' consolidated level of involvement has no effect on post-project Revised PSVT:R scores. H _a : [All, Female, or Male] students s who were only somewhat involved will have lower post-project Revised PSVT:R scores than more involved students.	Two-sample <i>t</i> -test
H ₀ : Student gender has no effect on Revised PSVT:R gains. H _a : Female students will have larger Revised PSVT:R gains than male students.	Two-sample <i>t</i> -test
H ₀ : Student gender has no effect on pre-project Revised PSVT:R scores. H _a : Female students will have lower pre-project Revised PSVT:R scores than male students.	Two-sample <i>t</i> -test
H ₀ : Student gender has no effect on post-project Revised PSVT:R scores. H _a : Female students will have lower post-project Revised PSVT:R scores than the male students.	Two-sample <i>t</i> -test
H ₀ : Students' gender has no effect on level of involvement. H _a : Female students will have greater involvement than male students.	Mann-Whitney U-test
H ₀ : Students' gender has no effect on course grade. H _a : Female students will have higher grades than male students.	Mann-Whitney U-test

Table 2
Results from paired *t*-tests.

Student Group	Pre-Project Revised PSVT:R Score		Post-Project Revised PSVT:R Score		<i>t</i>	<i>df</i>	<i>p</i>	Cohen's <i>d</i>
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>				
All Students	34.37	18.42	44.22	20.26	5.41	67	< .001	0.51
Gender								
Females	31.44	16.07	42.26	17.26	4.16	33	< .001	0.65
Males	38.40	20.12	47.10	23.01	2.99	29	.003	0.40
Involvement								
Somewhat Involved	33.15	18.44	41.74	20.52	3.45	46	< .001	0.44
Very Involved	39.00	17.61	52.24	17.36	6.05	16	< .001	0.76
Semester Grades								
Earned A	36.08	19.44	51.42	19.26	5.123	11	< .001	0.79
Earned B	34.22	17.06	45.22	21.89	2.752	22	.006	0.56
Earned C	36.26	21.72	41.32	20.53	1.552	18	.069	0.24
Earned D or F	31.20	14.05	40.80	16.48	2.527	9	.016	0.63

Note: Four (4) students preferred not to release demographic information and *p*-value is one-tailed.

engineering course plus a 3-D printed prosthetics project, and cannot isolate the effect of the project alone. Any significant gains in spatial skills, however, are considered to be a highly positive result of the study, as higher spatial skills are linked to improved outcomes in other academic fields in addition to engineering (Lohman, 1996; Maeda & Yoon, 2013; Sorby, 2009; Uttal et al., 2013; Wai et al., 2009). As the Revised PSVT:R scores were the only normal data collected, pre- versus post-project scores were analyzed with paired *t*-tests and the results are presented in Table 2. Figure 1 presents the average pre- and post-project Revised PSVT:R scores for all students, female students, male students, somewhat involved students, very involved students, and the students grouped by their semester course grade. Due to low sample size, students with Very Involved and Very Involved Plus scores were grouped as “Very Involved” and students earning a D or an F were grouped as “Earned D or F.” Because all of the alternate hypotheses regarding the pre- to post-project scores were that all the students would improve their spatial visualization skills (i.e., mental rotations), a one-tailed *p* is presented for assessing the significance of these results. Regardless of whether the student scores were examined as a whole, by gender, or by involvement level, the students had higher scores at the end of the project than they did at the start; these gains were larger than what could be expected from students taking the pre- and post-tests without intervention (Hopkins, Stanley, & Hopkins, 1990), and these changes were statistically significant. Further, grouping the students by their semester grade revealed that all but the students earning a C also had statistically significant improvements in their Revised PSVT:R scores. These increases are shown graphically in Figure 1, where the changes are greater than the variation noted by the standard error bars. The effect size of these differences (Cohen's *d*) ranges from 0.24 for the students earning a C, to 0.79 for the students earning an A. The small (Salkind, 2010) effect size of the improvement results

Figure 1. Pre-project versus post-project Revised PSVT:R scores by student group.

for students earning a C is not surprising considering the lack of statistical significance between the pre- and post-project scores. The other effect sizes range from medium to large (Salkind, 2010) effect, with the students who were very involved or earning an A having large effect sizes (0.76 and 0.79, respectively). As the three groupings of gender, involvement, and semester grades represent three ways to categorize the same group of students, there is every possibility that the students who were very involved also earned high grades in the course (most educators would likely anticipate such an association). Either way of assessing effort on this project (participation score or semester grade) shows a trend that putting more effort into activities that can improve spatial skills nets a greater improvement in spatial skills. This observation is in line with the findings of Sorby and Baartmans (2000) that spatial skills can be taught within a semester in order to help students catch up with their peers.

Regression Analysis of Factors Contributing to Post-Project Revised PSVT:R Scores

A multiple linear regression was calculated to predict post-project Revised PSVT:R scores based upon centered pre-project Revised PSVT:R scores, centered semester grades, whether the students were very involved (involvement levels 2 + 3), whether students were female, and three interaction variables: Very Involved X Centered Grades, Female X Very Involved, and Female X Centered Grades. A significant regression equation was found ($F(7,56) = 8.768, p < .001$), with an R^2 of .523. As shown in Table 3, only the centered pre-project Revised PSVT:R scores were significant predictors of post-project Revised PSVT:R scores. As the literature indicates that differences in initial Revised PSVT:R scores are often the result of some of the other predictor variables, such as being female (Sorby, 1999, 2000, 2009; Maeda & Yoon, 2013; Reilly et al., 2017),

Table 3
Regression analysis results of factors contributing to post-project Revised PSVT:R scores.

	<i>B</i>	<i>SE B</i>	β	<i>p</i>
<i>Intercept</i>	42.01	3.17		< .001
<i>Centered Pre-Project</i>	0.69	0.11	.63	< .001
<i>Centered Semester Grade</i>	0.46	0.26	.27	.075
<i>Very Involved</i>	4.51	8.31	.10	.590
<i>Female</i>	-0.97	4.57	-.02	.833
<i>Very Involved X Centered Grade</i>	0.37	0.53	.10	.487
<i>Female X Very Involved</i>	-3.00	9.54	-.06	.754
<i>Female X Centered Grade</i>	-0.56	0.36	-.23	.130

the pre-project scores are expected to already account for difference amongst students' varying initial scores. As such, the dominance of pre-project scores in the prediction of post-project scores is not surprising and additional analysis was conducted in order to explore the potential of additional associations between the variables.

Correlations with Project Involvement and Semester Course Grades

To further examine the extent to which students' gender, involvement, or semester grade influenced their pre- or post-project Revised PSVT:R scores, their Revised PSVT:R gains, or their semester grade, bivariate correlations were conducted using both Spearman's rho and Kendall's tau tests. The results of these tests are presented in Table 4. As greater involvement or higher grades were hypothesized to correlate with an increase in gains, pre- or post-project scores, or grades (for the correlation with increased involvement), one-tailed significance was calculated. Throughout Table 4, positive correlation coefficients, r_s , indicate that there were positive associations between variables, but only significant results are discussed.

For all students, there was a statistically significant correlation between increasing levels of involvement and increased pre- and post-project Revised PSVT:R scores, which are shown graphically in Figure 2. This trend held for the female students as well (Figure 3), but was too weak of an association to be statistically significant for the male students. While these correlations are statistically significant, the strength of individual relationships between the

Table 4
Correlations between involvement or course grade with pre- and post-project Revised PSVT:R scores, Revised PSVT:R gains, and with semester grade.

	<i>Revised PSVT:R Gains</i>		<i>Revised PSVT:R Pre-Project Score</i>		<i>Revised PSVT:R Post-Project Score</i>		<i>Semester Grade</i>	
	r_s	<i>p</i>	r_s	<i>p</i>	r_s	<i>p</i>	r_s	<i>p</i>
Involvement – All Students								
Spearman's rho	.15	.113	.22	.028*	.23	.033*	.40	< .001**
Kendall's tau	.13	.113	.19	.026*	.19	.031*	.33	< .001**
Involvement – Female Students								
Spearman's rho	.05	.387	.36	.012*	.30	.040*	.36	.014*
Kendall's tau	.04	.394	.31	.012*	.26	.039*	.30	.015*
Involvement – Male Students								
Spearman's rho	.22	.126	.16	.174	.25	.088	.43	.004**
Kendall's tau	.18	.128	.13	.176	.21	.086	.35	.005**
Semester Grade – All Students								
Spearman's rho	.19	.065	.24	.021*	.23	.033*		
Kendall's tau	.13	.073	.18	.016*	.15	.043*		
Semester Grade – Female Students								
Spearman's rho	.11	.264	.26	.057	.18	.156		
Kendall's tau	.05	.338	.21	.039*	.11	.181		
Semester Grade – Male Students								
Spearman's rho	.32	.043*	.32	.030*	.43	.008**		
Kendall's tau	.21	.053	.23	.026*	.30	.011*		

* Correlation is significant at the 0.05 level (1-tailed).

** Correlation is significant at the 0.01 level (1-tailed).

Figure 2. Revised PSVT:R scores versus level of involvement—All students.

Figure 3. Revised PSVT:R scores versus level of involvement—Female students.

independent variables and the dependent variables are weak for the overall student group and moderate for the females when analyzed separately. Revised PVST:R pre- and post-project scores for the overall student group each account for only 5% of the variation in involvement ($r_s^2 = .050$ and $.053$, respectively). When looking only at the female students, student involvement has a moderate association with the Revised PVST:R pre- and post-project scores, and this correlation accounts for a greater amount of variation: 13% and 9 %, respectively ($r_s^2 = .130$ and $.090$, respectively). The small number of male students who were Very Involved or Very Involved Plus Personal Time, which are involvement levels 2 and 3, ($n = 5$) could be the reason why the associations between involvement and Revised PSVT:R scores and gains were not significant.

Semester grades were tests for correlation with pre- and post-project Revised PSVT:R scores, Revised PSVT:R gains, and with student involvement. These tests had positive correlation coefficients, supporting the alternative hypotheses that there were positive associations between

Figure 4. Revised PSVT:R scores versus semester grade—All students.

Figure 5. Revised PSVT:R scores versus semester grade—Male students.

each variable pair, but not all of these associations were statistically significant. For the student group as a whole (Figure 4) and for male students (Figure 5), there was a statistically significant correlation between semester grades and their pre- and post-project Revised PSVT:R scores. While these correlations were statistically significant, the strength of the relationships are weak in that they only account for about 5% of the variation in the student's grades for the overall group ($r_s^2 = .058$ and $.053$ for the pre- and post-project scores, respectively). When analyzing the male students separately, the associations have moderate strength in that they account for 10% or 18% of the variation in students' grades for the pre- and post-project scores, respectively ($r_s^2 = .102$ and $.185$, respectively). The bivariate correlation between Revised PSVT:R gains and semester grades was also statistically significant for male students (Figure 6), although only with a Spearman's rho test. This positive association had moderate strength and so it accounted for about 10% in the variation of male students' Revised PSVT:R gains ($r_s^2 = .102$).

The correlations between student involvement and students' semester grades were statistically significant regardless of grouping by all, female, or male students (Figure 7).

Figure 6. Revised PSVT:R gains versus semester grade—Male students.

Figure 7. Semester grade versus level of involvement.

These associations were moderate in strength and so accounted for 13% to 18% of the variation in students' semester grades ($r_s^2 = .160, .130, \text{ and } .185$ for all, female, and male students, respectively). The observation that increasing levels of student involvement correlate with increasing grades would not be surprising to any educator.

As the number of students who were in the Very Involved Plus Personal Time group, which was coded as involvement level 3, was small ($n = 3$), these students were grouped with the other Very Involved students (level 2) for analysis of differences between students of different involvement levels in their Revised PSVT:R gains and pre-project or post-project scores. As the Revised PSVT:R data were normal and the condensed involvement levels were used to sort the data into two independent samples, differences in these groups were examined with two-sample t -tests that assumed an unequal variance between the groups (Pett, 2016). Table 5 presents the results of these t -tests, and Figure 8 displays the average Revised PSVT:R gains and pre- and post-project scores for the condensed

Figure 8. Revised PSVT:R gains, pre-project scores, and post-project scores by consolidated involvement group for all, female, and male students.

Table 5
Revised PSVT:R results of two-sample t -tests between involvement levels.

	Somewhat Involved (level 1)			Very Involved (levels 2 & 3)			<i>t</i>	<i>p</i>	Cohen's <i>d</i>
	<i>n</i>	<i>M</i>	<i>SD</i>	<i>n</i>	<i>M</i>	<i>SD</i>			
<i>All Students</i>									
Gains	47	8.60	17.10	17	13.24	9.02	1.40	.084	.34
Pre-Project Score	47	33.15	18.44	17	39.00	17.61	1.13	.128	.32
Post-Project Score	47	41.74	20.52	17	52.24	17.36	1.88	.032*	.55
<i>Female Students</i>									
Gains	22	10.45	17.75	12	11.50	9.37	0.19	.426	.07
Pre-Project Score	22	27.86	15.49	12	38.00	15.62	1.82	.039*	.65
Post-Project Score	22	38.32	16.81	12	49.50	16.31	1.87	.035*	.68
<i>Male Students</i>									
Gains	25	6.96	16.70	5	17.40	7.34	2.23	.022*	.81
Pre-Project Score	25	37.80	19.84	5	41.40	23.66	0.36	.361	.16
Post-Project Score	25	44.76	23.23	5	58.80	19.94	1.26	.110	.65

* Correlation is significant at the 0.05 level (1-tailed).

involvement groups for all students grouped together and separated by gender. Note that these tests were conducted using the results from students who took both the pre- and post-project Revised PSVT:R, and whose involvement level was known in order to characterize changes resulting from the project by consolidated involvement level. These results for all students show that the students who were Very Involved had statistically significantly higher Revised PSVT:R post-project scores than the Somewhat Involved students. This difference had a medium effect size (Cohen's $d = .56$). The Very Involved students had higher Revised PSVT:R pre-project scores and gains than the Somewhat Involved students, but these higher scores and larger gains were not statistically significant. For these two results without statistical significance, these results had small effect sizes (Cohen's $d = .34$ and $.33$, for Revised PSVT:R gains and pre-project scores, respectively). Figure 7 graphically shows the wider difference for the post-project scores between the consolidated involvement groups than for the pre-project scores or gains.

When further examining the influence of involvement on Revised PSVT:R scores by gender, which is also shown in Table 5 and Figure 8, the trends are somewhat different between female and male students. Female students in the two consolidated involvement groupings had statistically significantly different Revised PSVT:R scores, both pre- and post-project, with medium to medium-large effect sizes (Cohen's $d = .65$ and $.68$, respectively). The female students in these two involvement levels had similar gains in spatial skills over the course of the project, as reflected in the negligible difference in their Revised PSVT:R gains, including a tiny effect size (Cohen's $d = .07$). Thus, while female students overall showed statistically significant gains in spatial skills (Table 2 and Figure 1), their level of involvement did not appear to influence the effectiveness of the intervention. Male students, however, did not show statistically significant differences between involvement levels for pre- and post-project Revised PSVT:R scores; however, there is a statistically significant difference between the involvement groups in the size of

their Revised PSVT:R gains, with the more involved students experiencing the greater gains. This result has a large effect size (Cohen's $d = .81$). The small number of male students who were very involved in the class ($n = 5$) could be why this significant difference in gains did not result in statistically different post-project Revised PSVT:R scores, although the very involved male students did have higher average post-project scores than the somewhat involved male students, and this difference had a medium effect size (Cohen's $d = .65$). The differences in Revised PSVT:R gains between the involvement groups indicates that the male students' level of involvement appeared to influence the magnitude of their benefit from the intervention.

Differences Among Female and Male Students

Table 6 presents the results of the two-sample t -tests, assuming unequal variances to compare the differences in the female and male students. The table and Figure 9 present the Revised PSVT:R gains as well as the pre- and post-project Revised PSVT:R scores for the students who

Figure 9. Revised PSVT:R scores and gains by gender.

Table 6
Results of two-sample t -tests between genders.

	Female Students			Male Students			t	p	Cohen's d
	n	M	SD	n	M	SD			
Revised PSVT:R Gains	34	10.82	15.17	30	8.70	15.93	-0.54	.294	.14
Revised PSVT:R Pre-Project Score (paired data)	34	31.44	16.07	30	38.40	20.12	1.52	.068	.38
Revised PSVT:R Post-Project Score (paired data)	34	42.26	17.26	30	47.10	23.01	0.94	.176	.24
Revised PSVT:R Pre-Project Score (all pre-tests)	38	29.11	17.48	36	38.00	19.55	2.06	.022*	.48
Revised PSVT:R Post-Project Score (all post-tests)	34	42.26	17.26	31	47.10	22.63	0.96	.170	.24

* Difference is significant at the 0.05 level (1-tailed).

took both the pre- and post-project measures. The table and figure also present the pre- and post-project scores for all students who took the pre- or post-project Revised PSVT:R assessments, respectively. The data were examined with both groupings of students to look at both the results of the project's influence and the effect on the student averages for students leaving the school (unenrolling from the school prior to study/project completion). One student, a male, did join the class during the project period. Of the four female students who left the school during the project, three had initial Revised PSVT:R scores of 0 and one of 37. Looking at the pre- and post-project results for students who took both measures (noted as paired data), the male students did have higher average Revised PSVT:R scores both pre-and post-project, but these differences are not statistically significant. The pre-project scores for this group did have a larger effect size than the post-project scores (Cohen's $d = .38$ and $.24$, respectively) indicating that the groups of data had less overlap in the pre-project scores than the post-project scores. When considering all students who took either the pre- or post-project assessment (noted as "all" on the figure), the male students' average pre-project score was statistically significantly higher than that of the female students, with a medium effect size (Cohen's $d = .48$). The post-project data are nearly identical with or without the inclusion of results from the one male student who joined the class during the project. The female students had larger average Revised PSVT:R gains than the male students, with a small effect size (Cohen's $d = .14$), although this difference was not statistically significant. Results from the literature indicate that all researchers should anticipate female students coming into any study of spatial skills to have, on average, lower pre-intervention Revised PSVT:R scores than their male peers (Sorby, 1999, 2000, 2009; Maeda & Yoon, 2013; Reilly et al., 2017). That trend was observed again here, although when excluding results from the four female students with very low scores that withdrew from high school during this study, the difference was not statistically significant (paired data results). The gap between male and female student performance on the Revised PSVT:R instrument did narrow; this is also supported by literature, which has indicated that interventions to strengthen spatial skills can help students catch up with their peers (Brudigam & Crawford, 2012; Hungwe, et al., 2014; Sorby & Baartmans, 2000).

Table 7 presents the results of the Mann-Whitney U-tests to compare differences in the female and male students. While the female students have a higher average involvement level than the male students, as shown in Figure 10, this difference is not statistically significant, although it has a medium to small effect size ($\theta = .43$). The female students also had higher average course grades than the male students, as shown in Figure 11. This difference is statistically significant with a medium to small effect size ($\theta = .38$).

Interpretation/Discussion

Overall Increase on Revised PSVT:R Post-Project

In line with our primary hypothesis, all students' Revised PSVT:R scores increased from pre- to post-project (see Table 2). Additionally, this gain was statistically significant for all groupings except the grouping of students who earned a C in the course. When using the same test pre- and post-intervention there is always a risk that observed score improvements are due to the participants' increased familiarity with the measure. Hopkins and colleagues (1990) state that this increase can be as much as $0.2*SD$ of the initial score. As such, the difference in pre- to post-project Revised PSVT:R scores were checked against this $0.2*SD$ threshold. All gains in Revised PSVT:R scores were greater than this level, indicating that the observed gains were from more than increased familiarity with the instrument; rather, the students' spatial visualization skills did improve over the course of this nine-week project. This overall increase is in line with other similar research studies that integrated spatially-rich curricula with secondary populations (Brudigam & Crawford, 2012; Ernst & Clark, 2009; Hungwe, et al., 2014; Onyancha et al., 2009; Sorby et al., 2003), which indicates that the novel integration of the collaborative hands-on 3-D printed prosthetic project can positively impact students' spatial visualization skills.

Connections Between Project Involvement and Overall Course Grades

Higher levels of project involvement had a positive correlation to the students' initial Revised PSVT:R scores, as well as a positive correlation to students' grades in the course (see Table 4). From examining the pre- to post-test

Table 7
Results of Mann-Whitney U-tests between genders.

	<i>Female</i>			<i>Male</i>			<i>Mann-Whitney</i>		
	<i>n</i>	<i>M</i>	<i>SD</i>	<i>n</i>	<i>M</i>	<i>SD</i>	<i>z</i>	<i>p</i>	θ
Involvement	38	1.34	0.53	37	1.22	0.53	-1.41	.079	.43
Course Grade	38	78.89	12.69	37	74.35	12.61	-1.81	.035*	.38

* Correlation is significant at the 0.05 level (1-tailed).

Figure 10. Average level of involvement by gender.

Figure 11. Average semester grade by gender.

scores for the consolidated involvement groups (see Table 5), it can be seen that the two groups started with nearly the same spatial visualization skills: The Revised PSVT:R scores were not statistically significantly different for the overall student group nor for the male students, although the Very Involved students did start at a higher level than the Somewhat Involved students. The difference in pre-project Revised PSVT:R scores was statistically significant for female students when analyzed separately from the male students. While the consolidated involvement groups had higher post-project Revised PSVT:R scores, the Very Involved group had a greater increase in their mean post-project score than the Somewhat Involved students. The difference between the post-project scores for these involvement groups is statistically significant and higher for the Very Involved students when analyzed for all students together and the female students separately. The difference between the involvement groups for the male students' post-project Revised PSVT:R grades was not statistically significant, despite a 14-point difference between means. The small

number of males in the Very Involved group ($n = 5$) is likely the reason that these results were not statistically significant. Each student grouping (all, female, and male) had larger gains in Revised PSVT:R. Scores were larger for the Very Involved students than for the Somewhat Involved students; however, the difference in the mean of these gains was only statistically significant for the male students. This widening difference indicates a trend; that is, greater participation in the semester project could lead to larger gains in spatial visualization skills, as opposed to more limited engagement. Due to the collaborative nature of this 3-D printed prosthetics project within the existing curricula, this study is unique in its ability to show larger gains in spatial visualization skills due to higher levels of involvement in the project. Previous research does not exist to corroborate this finding.

On average, female students had higher grades than male students, but the differences in level of involvement were not statistically different between the genders. According to Sorby and Baartmans (2000), the PSVT:R test was a strong predictor of final score in engineering design graphics, as determined through a multiple regression analysis. However, this study found that the female students had lower PSVT:R scores (although not with statistical significance) and higher semester grades (with statistical significance), which goes against the typical trend found in other studies that focused solely on engineering design graphics content. That said, Brudigam and Crawford (2012) reported on similar populations; however, they did not report differences in course grades based on gender.

Reducing the Spatial Visualization Gender Gap on the Revised PSVT:R

One of the primary foci of this study was the spatial visualization gender gap that is commonly reported in the literature. As shown in our results, female students had lower Revised PSVT:R scores than their male peers before the project and experienced larger gains in their Revised PSVT:R scores pre- to post-project (although the mean male student score was still higher than the mean female student score as seen in Table 2 and Table 6). If the pre-project scores for all students are analyzed, then the initial scores show the gender gap to be statistically significant. If the scores of the students who left the school (and thus did not take the post-project test) are excluded from the pre-project average, then the initial gender gap is not statistically significant, although the male students still have a higher mean score than the female students. Female students did have larger gains than male students, although the difference was not statistically significant. Still, the observed gender gap, whereby male students are more likely to have higher spatial visualization and mental rotation skills, shrank during this nine-week project regardless of whether the pre-test scores for students who did not

complete the post-test (due to unenrollment in the school prior to the post-test administration) were included in the analysis. The trend of the closing gender gap, which is evidenced by the female and male students' mean scores, suggests that a hands-on project can help female students to catch up on their spatial visualization and mental rotation skills. This trend is in line with the reduced spatial visualization gender gap reported in previous research (Brudigam & Crawford, 2012; Hungwe, et al., 2014).

Limitations

Some students enrolled/unenrolled at the school during the study; therefore, the initial 85 students was reduced to 64 students who completed both pre-/post-test administrations of the Revised PSVT:R and provided demographic information. An additional limitation is the fact that race/ethnicity and ESL status were not available for the sampled population, and so this study was not able to include those variables in connection with spatial visualization and mental rotation skills. As there was no separate control group that received the same engineering course without the 3-D printed prosthetics project, this data is only able to measure the combined effect of the engineering course plus a 3-D printed prosthetics project, and cannot isolate the effect of the project alone. The trends revealed through this study need to be confirmed by replicated studies.

Conclusion

Prior research shows that it is possible to increase spatial visualization and mental rotation skills in order to reduce the gender gap through a prescribed training program (Hungwe, et al., 2014; Sorby, 1999, 2000, 2009; Sorby & Baartmans, 2000; Uttal et al., 2013). However, little research exists that examines the impact of novel projects that are integrated within existing curricula. Students involved in this study had gains on Revised PSVT:R scores over the nine-week project without participating in a prescribed training program, but instead a novel collaborative 3-D printed prosthetics project embedded within their existing curriculum. Across genders, students who were more involved in the project had greater gains of spatial visualization skills (Revised PSVT:R scores) than students who were less involved. While the female students had greater gains than male students, which worked on closing the gender gap in performance, the difference in these gains during the semester was not statistically significant. The addition of a novel spatially rich hands-on project did show a positive impact on students enrolled in this 9th grade "Beginning Concepts in Engineering" course, which is similar to the impact reported by the use of specialized spatial visualization curricula interventions (Hungwe, et al., 2014) and engineering graphics curricula (Brudigam & Crawford, 2012).

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