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Toward a Broader Understanding of Spatial Ability in CAD Education

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Abstract. Spatial ability has long been considered important in CAD education. However, spatial ability is not a unitary construct, but a family of a variety of different skills. The choice of which spatial tests are thought to measure spatial abilities in CAD education is rarely called into question, and the Purdue Spatial Visualization Test (PSVT:R) is among the most popular. In the present study, we used a spatial test from apparel design with a group of students enrolled in a CAD course in an engineering program. While male students scored higher than female students on the PSVT:R, female students outperformed males on the Digital Apparel Spatial Visualization Test (DASVT). Students with relevant background experience scored better than students without background experience on both tests. Our results suggest that the current approach to spatial testing in CAD education may be taking an overly narrow view of the spatial construct, particularly with the growing interest in CAD applications to soft goods design and apparel design.

Keywords: spatial ability, CAD education, PSVT:R, apparel design, STEM education
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1 INTRODUCTION

Though spatial skills have long been considered important in CAD education, the spatial assessments used tend to focus on a very narrow set of skills such as mental cutting and mental rotation. Spatial tests have also been developed in fields that are not typically considered to be part of STEM, such as apparel design and interior design, but spatial tests that draw their content from disciplines like engineering are typically used to assess "generalized" spatial ability. Mental rotation tests, which utilize imagery from drafting or engineering drawing, are probably the most well-known example. Using such tests as a stand-in for "general" spatial ability is somewhat misleading since spatial ability cannot be understood as a single construct. Instead, spatial ability is really an umbrella term covering several somewhat separate abilities [10,18,22].

Computer-aided design is now widely used in disciplines outside of engineering, such as apparel design, and is an essential component of the training of apparel design students [1,19,50]. Patternmakers in apparel design use CAD systems to sew 2D CAD patterns digitally to create 3D virtual prototypes of garments and soft goods [7]. Other disciplines besides apparel design are also increasingly using CAD to model "soft" objects. Industrial design and engineering teams often design soft goods or products that have both soft and hard components. With the increasing prevalence of online shopping, product teams often create digital renderings for marketing and sales purposes, as this can be more cost effective and efficient, and allow for more artistic freedom than taking photographs of prototypes or final products. Thus, the CAD skills that needed in industries like product and industrial design are increasingly diverse. Figure 1 shows examples of product renderings of 3D models of soft goods or hard goods with soft components.

Figure 1: Renderings of 3D models of products with soft components. From left to right: pouf chair by Linda Bui, Meta Quest 2 VR headset by Tim Zarki, Nike shoe rendering by Kristin Bartlett.

Popular spatial assessments like the PSVT:R do not capture the broad range of spatial thinking needed to model objects like those shown in Figure 1. A spatial test from apparel design may be more suitable. In the present study, we explore what would happen if we changed the context of spatial problem solving by using a spatial test derived from the apparel design discipline with a group of undergraduate engineering students enrolled in a CAD course. The student sample is representative of the students who are typically assessed with instruments like the Purdue Spatial Visualization Test (PSVT:R). We used the Digital Apparel Spatial Visualization Test (DASVT), an updated version of the original Apparel Spatial Visualization Test (ASVT). We explore the question of whether typical assessment of spatial thinking in CAD education might be using an overly narrow conception of "spatial ability."

2 BACKGROUND

2.1 Mental Rotation Tests and their Association with Content from Engineering Graphics

Much of our current understanding of spatial skills is derived from experiments using psychometric tests. Researchers have identified that spatial skills cannot be reduced to one single factor or skill [10,18,22], and a variety of spatial tests exist which are thought to measure different spatial skills. One often-measured spatial skill is 3D mental rotation. Mental rotation originally gained attention with Shepard and Meltzer's 1971 experiment in which they showed subjects pairs of drawings of shapes in different rotated positions, and the subjects were asked to judge whether the shapes were the same or not [34]. An example stimulus from their experiment is shown in Figure 2.

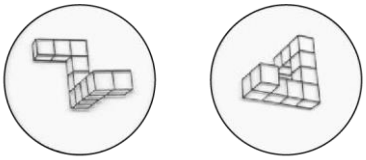

Figure 2: Example stimulus from Shepard & Metzler's (1971) experiment (Shepard & Metzler, 1971).

Vandenberg and Kuse later created the Mental Rotation Test (MRT) as an instrument for group administration, which used similar shapes but in a multiple choice format [44]. An example problem from the MRT is shown in Figure 3. In this question, the test-taker must look at the figure on the far left and determine which two of the four answer choices are the same shape rotated into a different position.

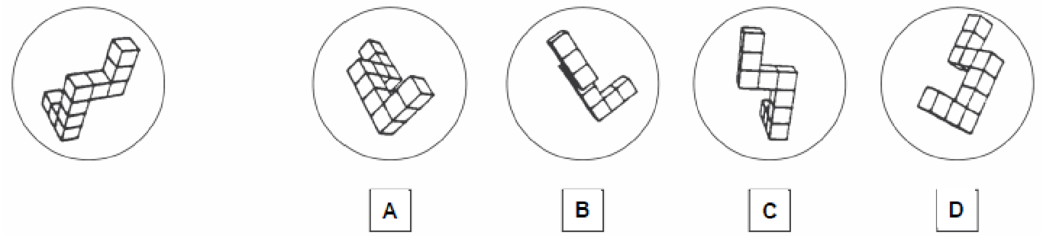

Figure 3: Example question from MRT (Vandenberg & Kuse, 1978). Correct answers are B and D.

The Purdue Test of Spatial Visualization: Rotations [17] is another popular test of mental rotation. A revised instrument was created in 2011 to correct errors in the original version [47]. While the MRT is more commonly used in the social sciences, the PSVT:R is most often used to assess spatial ability in the context of engineering and STEM, for example: [8,14,20,27,33,38–40,49]. Educators use the PSVT:R to predict performance in their courses, to validate training courses which are designed to improve spatial ability, or to screen students for participation in remedial spatial skills classes [24]. An example problem from the Revised PSVT:R is shown in Figure 4. The test-taker must determine the rotation that occurs to transform the shape in the top left into the position shown in the top right. Then, they must apply the same transformation to the shape in the middle row and decide which of the multiple-choice answers shows the position of that shape after the rotation has been applied.

Tests like the MRT and PSVT:R use isometric drawings to present the mental rotation problems, which can lead to confusion. In perspective drawing, which naturally replicates human vision, lines on geometric shapes are seen to be converging at vanishing points, making things appear smaller as they go back in space. In contrast, lines in isometric or axonometric drawings are kept parallel as they go back in space, which can make the drawings less clear for the viewer since the drawings do not intuitively convey a sense of space. These visual problems may make tests like the PSVT:R and MRT less accurate for measuring mental rotation skills [4]. Item difficulty on the PSVT:R is not explained by degree of rotation alone, and the complexity of the 3D shapes may also contribute to item difficulty [48]. Many of the shapes on the PSVT:R do not naturally look like 3D shapes, which may limit the instrument's ability to be an assessment of mental rotation alone [5].

2.2 Spatial Resting in Apparel Design

Though spatial skills have been considered important in mechanical disciplines for the past century, the role that spatial thinking plays in non-STEM fields has received attention only much more recently. Spatial thinking is now recognized to have importance in disciplines such as interior design [11] and apparel design [37,45,46], which also require a mastery of understanding transformations of objects in 3D space.

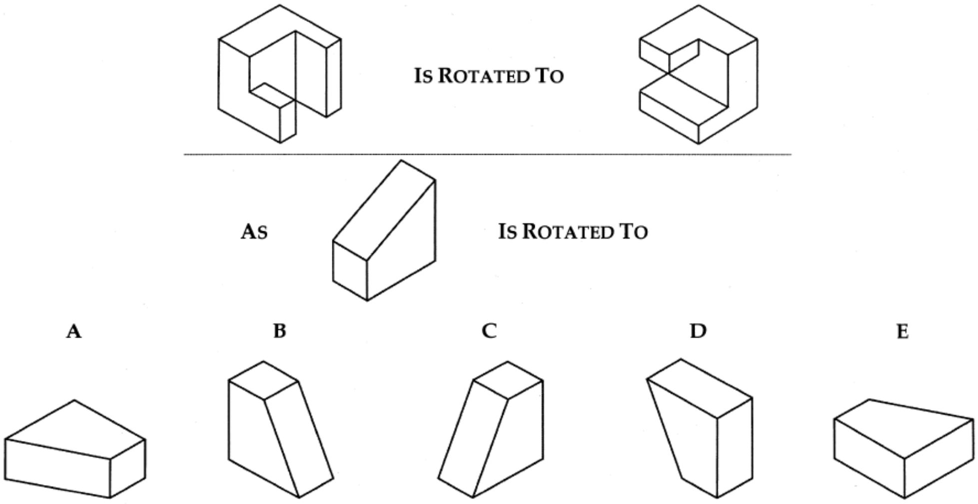

Figure 4: Example problem from the revised PSVT:R (Yoon, 2011). Correct answer is B.

For apparel design in particular, practitioners need to be able to understand how shapes in a flat pattern will come together into a flexible, 3D garment or soft good or how a dart in the fabric will affect the resulting 3D shape [45]. In the case of spatial problem-solving in apparel design, shapes must be not only mentally rotated, but also manipulated in other ways. A designer must be able to visualize how the fabric will fall into place depending on how and where it is attached to the other pieces of fabric.

The Apparel Spatial Visualization test was created in 1999 as a way to measure spatial skills that are specific to apparel design [45]. The test questions show a sewing pattern, and the test taker then needs to select the garment which corresponds to the pattern [45]. The Digital Apparel Spatial Visualization Test (DASVT) was recently created as an update of the Apparel Spatial Visualization Test [37]. An example question from the DASVT is shown in Figure 5.

In the original publication on the DASVT [37], students rated this test as easier than the Surface Development Test (SDT) and ASVT. Scores on the DASVT were also found to be positively correlated with the SDT and ASVT [37]. The DASVT has been validated with apparel design students but has not been used yet with students in other academic programs. While garment construction is not considered part of STEM, there are many similarities to engineering, and using 2D pieces to create a 3D shape is a task that many engineering students would encounter in their studies or professional careers. Fabric is certainly not foreign to engineering either, as it appears in parachutes, sails, awnings, automotive interiors, protective equipment, military equipment, consumer goods, and more. The terms fabric engineering and textile engineering are commonly used to describe the technical jobs of creating fabrics for specific purposes. Thus, the skills assessed in the DASVT may have relevance to disciplines like engineering and industrial design.

2.3 Role of Experience in Spatial Ability Tests

The role of experience in spatial test performance has long been a topic of discussion. In 1967, Sherman introduced the hypothesis that the reason that men performed better than women on tests of spatial ability was not due to some biological difference, but due to differential training [35]. Recognizing that gendered socialization patterns led to different training and experiences for men and women, Sherman proposed that disciplines like drafting should be "de-sexed."

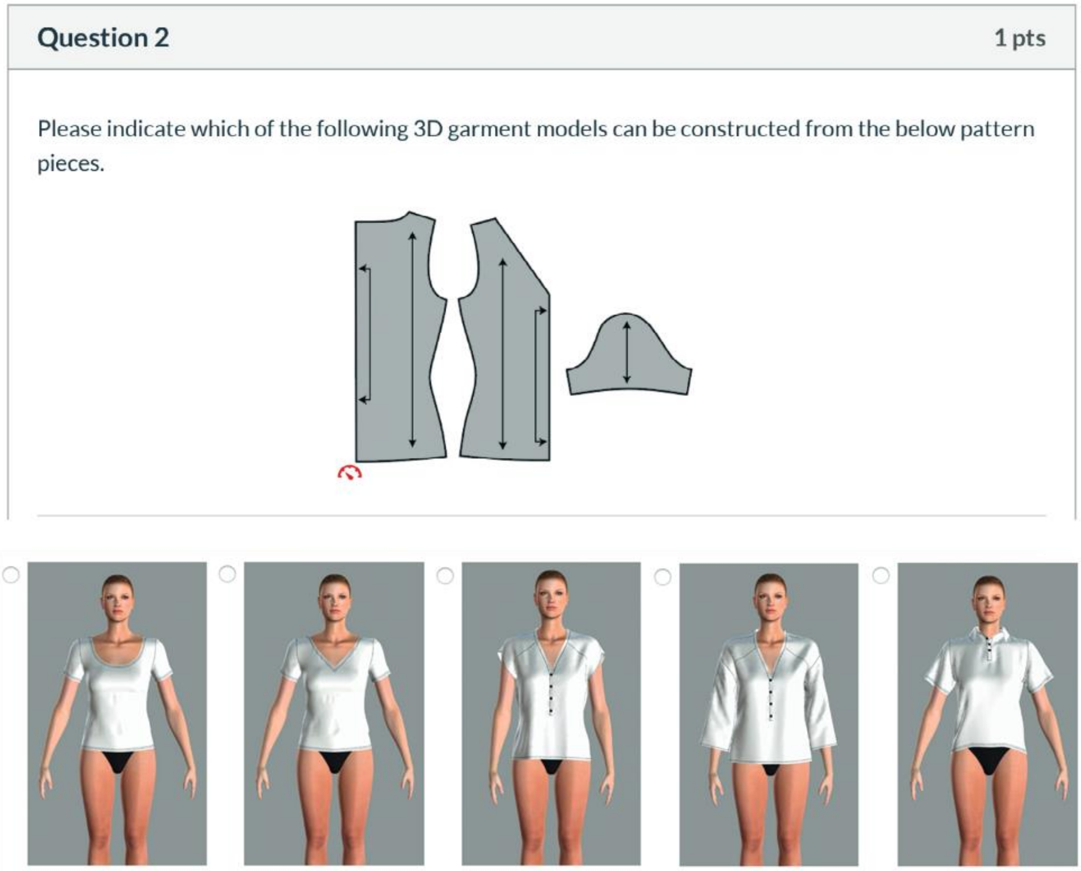

Figure 5: Example of a question from the DASVT. Though we have shown a static image here, in the actual test the images are animations in which the figure rotates 360 degrees around the z-axis so that all sides of the garment can be viewed. The correct answer is the second option.

While Sherman specifically referenced some graphics topics such as drafting, subsequent research focused quite heavily on differential play experiences, such as using Legos, Lincoln logs, blocks, video games, etc., and suggested that such experience led to improved spatial skills. Thus, it was argued that because boys were more likely to have these experiences, they tended to develop better spatial skills than girls [9,16,41].

In order to investigate Sherman's hypothesis that differential experiences contributed to gender differences in performance on spatial tests, "spatial activities questionnaires" were developed to assess what childhood activities may contribute to the development of spatial ability [29,36]. Baenninger and Newcome (1989) later performed a meta-analysis reviewing studies in two major areas: participation in activities thought to improve spatial ability (correlational studies using the aforementioned spatial activity questionnaires) and the use of training programs to improve spatial ability (experimental studies). They found that spatial activity participation was at least weakly correlated to spatial test performance, but not every activity on the surveys was actually shown to correlate with spatial ability on its own [3]. Thus, the spatial activities questionnaire may have made some incorrect assumptions about the nature of activities that actually contributed to high scores on spatial tests. Baenninger & Newcombe also found that both males and females improved performance on spatial ability assessments equally after training or practice, which was supported by a later meta-analysis by Uttal et al. [43]. Others found a relationship between children's play with Lego blocks and performance on a spatial ability assessment [9]. Baenninger and Newcome concluded that environmental input was necessary for development of both mathematical and spatial skill, and that boys were receiving this input at higher rates than girls.

Though past researchers have argued that the gender differences in spatial test performance were rooted in biological sex differences, multiple recent reviews demonstrate that this is not the case [6,30]. We have previously argued that the construct of spatial skills is co-constructed with gender and that some spatial tests were intentionally crafted to favor male performance due to a preconceived idea that men have better spatial skills than women [6]. We have advocated for a broader understanding of spatial ability that better includes the spatial skills required in disciplines traditionally associated with women, such as apparel design. The present work explores these ideas further.

3 METHODS

3.1 Study Participants

The participants in this study were 226 undergraduate students in an introductory CAD course at a public university in the Midwest United States. The students were all in various engineering majors. In this study, we define gender as a pattern of social relations which brings differences between bodies into social processes [12]. We do not view gender as a variable which itself causes differences, rather, patterns of socialization lead people of different genders to obtain different life experiences. The demographics of the participants are described in Table 1.

		Frequency	*Percent*
Gender	Male	164	72.6
	Female	56	24.8
	Nonbinary	3	1.3
	No response	3	1.3
Race	Asian	40	17.7
	Black/African American	5	2.2
	Hispanic/Latino	5	2.2
	Middle Eastern/N. African	3	1.3
	White/Caucasian	146	64.6
	More than 1 race	16	7.1
	Other	3	1.3
	No response	3	3.5

Table 1: Frequency distributions of participants by gender and race.

3.2 Materials

Study materials included the Revised PSVT:R [47] and the DASVT [37]. The PSVT:R contains 30 multiple-choice questions which all follow the same format as the example shown in Figure 4. The original DASVT contains 20 questions, however, we used one of the questions as an example tutorial question, and omitted the final question by mistake, meaning the version of the test given to participants contained 18 questions. All questions in the DASVT follow the same multiple-choice format as the example shown in Figure 5. Both tests were administered on the computer using Qualtrics software. Following the administration of each test, the participants were asked some basic survey questions about their prior experience with engineering graphics and textiles.

3.3 Research Questions

This study sought to answer the following research questions:
R1) Are there significant differences between female and male scores on the revised PSVT:R?
R2) Is there a significant difference in scores between people with and without engineering graphics experience on the revised PSVT:R?
R3) Does experience matter more for men or women on the revised PSVT:R?
R4) Are there significant differences between male and female scores on the DASVT?
R5) Is there a significant difference in scores between people with and without textile experience on the DASVT?
R6) Does experience matter more for men or women on the DASVT?
R7) Is there a significant correlation between scores on the DASVT and PSVTR?

3.4 Engineering Graphics Experience

Engineering graphics experience data was obtained from a survey question, which was phrased as follows: Have you ever been part of any clubs or extracurricular activities where you used skills like CAD and engineering drawing? We chose this question to use in the analysis over other similar survey questions (ex. past participation in a CAD course) because there was about a 50/50 split in the responses for this question, whereas others were less evenly split. Participation in clubs or activities in which they used CAD or engineering graphics was also thought to be a better question than asking about participation in a course, because a course may have been required and the student may or may not have interest in it. Participation in clubs or activities was thought to be more voluntary and more reflective of personal interest in the subject matter. The percentage of students who reported engineering graphics experience is shown in Table 2.

Graphics Experience	*Frequency*	*Percent*
Yes	107	46.3
No	124	53.7

Table 2: Engineering graphics experience.

3.5 Textile Experience

Textile experience data was obtained through a survey question. We asked participants this question: Do you have experience with any of the following: clothing construction, sewing, pattern making/pattern layout, soft goods design, CAD for clothing construction (eg. Marvelous Designer software). The question allowed the participants to check boxes for all answers that applied to them. If they answered “yes” to any of these items, they were coded as having Textile Experience. The percentage of participants who reported textile experience is shown in Table 3.

Textile Experience	*Frequency*	*Percent*
Yes	39	17.3
No	187	82.7

Table 3: Textile experience.

3.6 Measures – Revised PSVT:R

The mean score on revised PSVT:R was 23.01 with a standard deviation of 4.837. Descriptive statistics of the revised PSVT:R scores of different groups are shown in Table 4.

	No Experience	*Experience*

	N	*M*	*SD*	*N*	*M*	*SD*
Male	90	23.03	5.007	74	24.26	4.731
Female	30	20.10	4.421	26	22.69	3.988

Table 4: Descriptive statistics for scores on Revised PSVT:R.

The distribution of scores on the revised PSVT:R is negatively skewed, which is typical for scores on this instrument (for example: [23]). Additionally, the sample size of 226 is fairly large. The distribution is shown in Figure 6. There was no obvious violation of the assumption of equal variances.

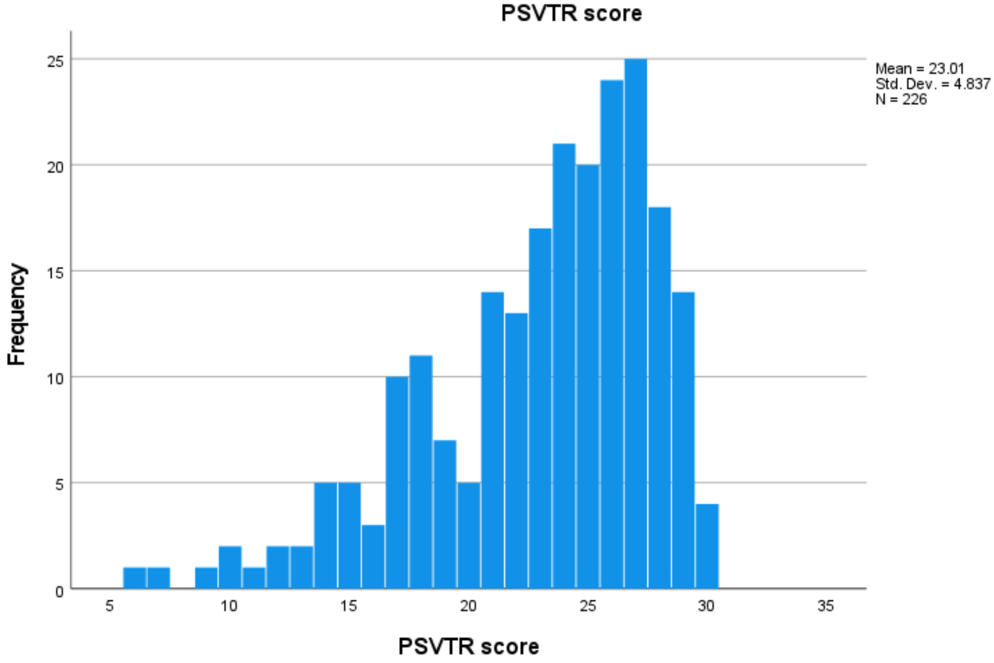

Figure 6: Score distribution on the Revised PSVT:R

We removed participants who spent less than 5 minutes or more than 40 minutes on the PSVT:R from our dataset. We also removed people who scored at or below chance (5 points or less). We did not use a time limit on the PSVT:R for two reasons, one, because the DASVT does not have a time limit, and two, because we were using some data from this study for another separate analysis which included looking at the time spent on each individual question.

3.7 Measures – DASVT

The maximum possible score is on the DASVT is 18 points, and scores are integers. People who scored below chance (under 4 points) have been removed from the data. There was no time limit given on the test, but the people who spent less than 3 minutes were removed, since the vast majority scored below chance, and people who spent more than 40 minutes were removed, since they were outliers from the group. The mean score on DASVT was 8.3 with a standard deviation of 3.1555. Descriptive statistics of group performance on the DASVT are shown in Table 5.

	No Experience			*Experience*		
	N	*M*	*SD*	*N*	*M*	*SD*

Male	151	7.54	2.766	13	8.69	3.425
Female	30	9.70	3.825	26	10.23	2.566

Table 5: Descriptive statistics for scores on Revised DASVT.

The distribution of scores on the DASVT was somewhat positively skewed (see Figure 7), however, the sample size of 226 is sufficiently large to continue with a factorial ANOVA. There was no obvious violation of the assumption of equal variances.

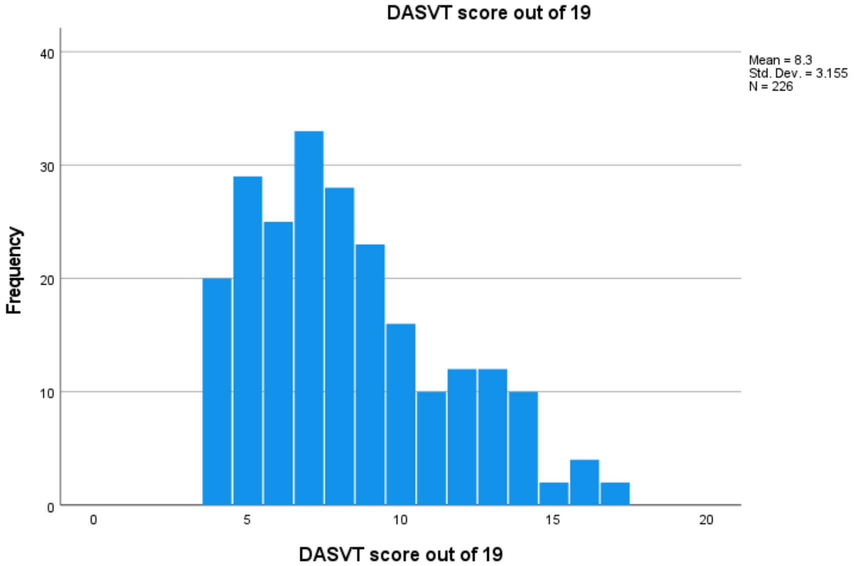

Figure 7: Score distribution of the DASVT.

3.8 Test Difficulty

The post-test surveys included Likert questions about test difficulty. The options were: 1 – extremely easy, 2 – somewhat easy, 3 – neither easy nor difficult, 4 – somewhat difficult, 5 – extremely difficult. The average rating for the DASVT was between somewhat difficult and extremely difficult (M = 4.23, SD = .779). The average rating for the PSVT:R was neither easy nor difficult (M = 3.06, SD = 1.009). Thus, the students in this sample considered the DASVT to be more difficult than the PSVT:R, which also appears to be reflected in the distributions of scores.

3.9 Analysis Method

We used two ANOVAs to answer the research questions. The first ANOVA was a 2X2 between subjects ANOVA. The between-subjects variables were engineering graphics activity participation (yes/no coded 1/2), and gender (female/male coded 1/2). The dependent variable was the score on the Revised PSVT:R. The second ANOVA was also a 2X2 between subjects ANOVA. The between-subjects variables were textile experience (yes/no, coded 0/1), and gender (female/male coded 1/2). The dependent variable was the score on the DASVT. Finally, we performed a correlation analysis to look for a correlation between scores on the revised PSVT:R and DASVT.

4 RESULTS

4.1 Results for PSVT:R

A two-way ANOVA yielded a significant main effect for gender on the PSVT:R score, $F(1, 216) = 9.384$, $p = .002$, such that the average score was significantly higher for men ($M = 23.59$, $SD = 4.908$) than for women ($M = 21.30$, $SD = 4.386$). There was also a main effect of experience on the PSVT:R score $F(1,216) = 6.754$, $p = .010$, such that the average score was significantly higher for people with experience ($M = 23.83$, $SD = 4.548$) than for people without experience ($M = 22.32$, $SD = 4.985$). The interaction effect was not significant, $F(1,216) = 0.869$, $p = .352$. Thus, reject the null hypothesis for research questions 1 and 2, but we fail to reject the null hypothesis for research question 3. Results of the Levene's test showed that the assumption of equal variances was not violated. The Partial η2 effect size for gender was .042 and for experience was .030. Results of the ANOVA are summarized in Table 6. The estimated marginal means plot is shown in Figure 8.

Predictor	**Sum of Squares**	***df***	**Mean Square**	***F***	***p***	**Partial η^2**
Intercept	84161.8	1	84161.800	3764.334	<.001	.946
Gender	209.813	1	209.813	9.384	.002	.042
Experience	151.005	1	151.005	6.754	.010	.030
Gender x Experience	19.434	1	19.434	.869	.352	.004
Error	4829.260	216	22.358			

Table 6: ANOVA table for Revised PSVT:R scores.

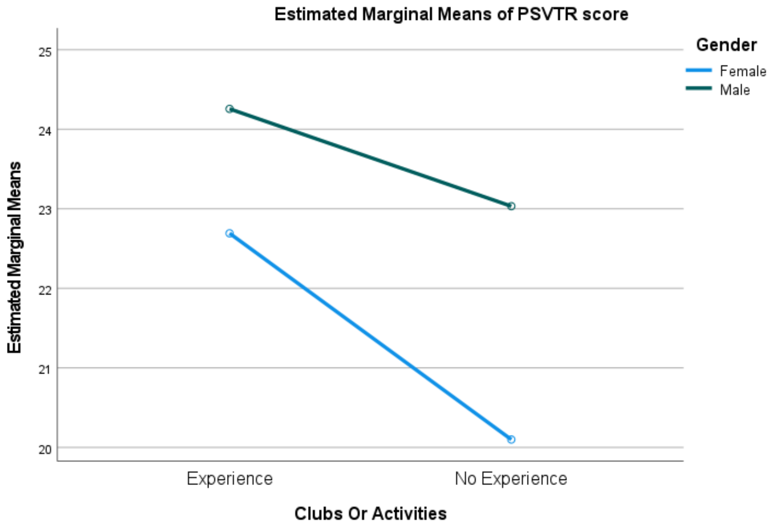

Figure 8: Estimated marginal means plot of PSVT:R scores.

4.2 Results for DASVT

A two-way analysis of variance yielded a significant main effect for gender on the DASVT score, $F(1, 216) = 10.116$ $p = .002$ such that the average score was significantly higher for women ($M = 9.95$, $SD = .439$) than for men ($M = 7.63$, $SD = 2.828$). There was not a significant main effect of experience on the DASVT score, though people with experience did score higher than people without experience $F(1, 216) = 2.091$, $p = .150$. The interaction effect was not significant, $F(1, 216) = 2.463$, $p = .283$. Thus, we fail to reject the null hypothesis for research questions 5 and 6, but we do reject the null hypothesis for research question 4. The Partial η^2 effect size for gender was .045. The Levene's test was not significant, indicating that we did not violate the assumption of equal variances. Results of the ANOVA are summarized in Table 7. The estimated marginal means plot for the DASVT scores is shown in Figure 9.

Predictor	**Sum of Squares**	***df***	**Mean Square**	***F***	***p***	**Partial η^2**
Intercept	8420.140	1	80.977	968.887	<.001	.818
Gender	87.911	1	8420.140	10.116	.002	.045
Experience	18.170	1	18.170	2.091	.150	.010
Gender x Experience	2.463	1	2.463	.283	.595	.001
Error	1877.155	216	8.691			

Table 7: ANOVA table for DASVT scores

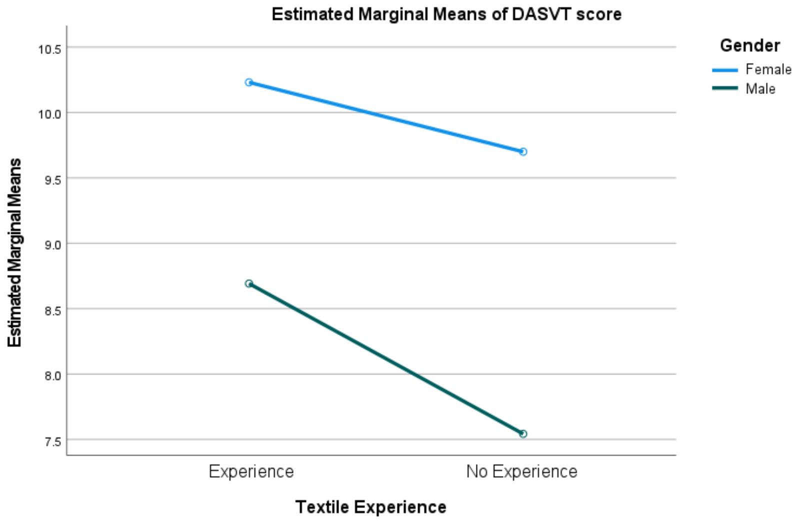

Figure 9: Estimated marginal means plot of DASVT scores.

4.3 Correlation between PSVT:R and DASVT

There was not a significant linear correlation between scores on the DASVT and PSVT:R, r(224) = .126, p = .059. Thus, we fail to reject the null hypothesis for research question 7.

5 DISCUSSION

In this study, we investigated the effects of gender and prior experience on two very different spatial tests, the PSVT:R and the DASVT. These two spatial tests were selected to represent a wider spectrum of the construct of spatial ability than what is typically assessed in STEM. The PSVT:R is often used in STEM and engineering to assess mental rotation ability. The DASV:T was created to assess spatial abilities specific to apparel design and requires visualization of complex 3D manipulations to imagine how a flat pattern becomes a 3D garment. The PSVT:R uses imagery derived from drafting whereas the DASVT:R uses imagery derived from apparel design. We used two-way ANOVAs for gender and experience on both instruments. Main effects of gender and experience were found on the PSVT:R, and a main effect of gender was found on the DASVT. A significant linear correlation between performance on the two tests was not found.

It was not surprising that men scored better than women on the PSVT:R, because other studies have found the same result [25]. However, no other studies have attempted to use a test from a non-STEM discipline alongside the PSVT:R. The original validation study of the DASVT used only female apparel design students [37]. In this study, we found that within the same group of undergraduate engineering students, male students outperformed female students on the PSVT:R, yet the reverse was true for the DASVT. In both cases, students with subject-matter experience scored higher than those without, although results were only statistically significant for the PSVT:R. Relatively few students in our sample had past textile experience, which may explain the non-significant result.

Measuring level of experience is challenging, and in this study, we did not attempt to measure experience in a precise way. We coded participants as having experience or not, but in reality, level of experience is a spectrum. We chose to use participation in clubs or activities which used engineering graphics topics like CAD and engineering drawing as the variable to measure "engineering graphics experience," but that may or may not have been the most relevant question to use. This question was selected to code for experience in part because it demonstrated a good 50-50 split between groups and in part because it was thought to represent a voluntary interest in the subject matter. But ultimately there may have been more accurate mechanisms to assess someone's representational competence with isometric graphics like those used in the PSVT:R. Similarly, there may have been more appropriate methods to assess someone's level of familiarity with the representations of fabric patterns used the DASVT in comparison with the questions that we used to gauge past textile experience.

The fact that no significant correlation was found on the two instruments is initially somewhat surprising. However, this fact can be explained by the fact that no single spatial factor exists, and there are a variety of different skills that all fall under the umbrella term of "spatial skills" [10,18,22]. Atit et al. argued that the spatial skills needed for non-rigid mental transformations are unique from those required for rigid transformations [2]. Our experiment offers evidence in support of this assertion, since the PSVT:R requires rigid transformation and the DASVT requires non-rigid transformations.

Another explanation for the lack of correlation between the two tests instead relates to graphics and representational competence. Stieff et al. suggested that "representational competence plays a moderating role in spatial thinking tasks…and may explain more variance in performance than mental rotation ability" [42]. By representational competence, Stieff and colleagues were referring to the level of familiarity with a discipline-specific style of imagery. Bartlett & Camba similarly suggested that the PSVT:R may not assess mental rotation skill alone because the difficulties in interpreting some of the graphics used in the instrument may introduce construct irrelevant variance [4,5]. Due to gendered patterns of socialization, men might be more familiar with isometric graphics like those used in the PSVT:R and women more familiar with sewing patterns and imagery of female clothing used in the DASVT. There is a possibility that gender differences on some spatial tests could have more to do with representational competence and/or graphics interpretation than actual spatial ability. This possibility is supported by studies which used real or virtual 3D objects rather than drawings of objects to measure mental rotation skill and did not find gender differences in performance [15,21,26,28,32].

5.1 Limitations

We acknowledge some of the limitations of our study. First, the group of students who participated are not representative of the general population. They were undergraduate engineering students who were mostly white and male. The sample size was only slightly over 200 people, which is not as large as some studies conducted with spatial instruments. Second, the DASVT is a new instrument and has not been extensively studied, though as we argue in this paper, spatial tests from non-STEM disciplines rarely see widespread use.

5.2 Future Work

The PSVT:R has commonly been used in engineering educational contexts and the DASVT was previously used in an apparel design context. Future work could repeat the current study in a student population not oriented toward engineering or apparel design, such as students from psychology or social sciences, or a mixed group of students from a variety of majors. As argued by Atit et al. (2013), non-rigid mental transformations like those employed to solve the DASVT receive much less attention than spatial skills like mental rotation, so future should continue to study a greater diversity of spatial constructs. Rather than homing in on mental rotation as a predictor of STEM success, it is recommended that future research examines a wider variety of spatial abilities and considers how these skills might be important for CAD education both inside and outside of STEM. Future work could also consider the impact of cultural background and technology on spatial test performance or make use of longitudinal studies.

6 CONCLUSION

We endeavored to find a relationship between gender and past experience in two spatial tests: the revised PSVT:R and the DASVT. Significant main effects of gender and experience were found for the revised PSVT:R, but no interaction effect. A significant main effect of gender was found for the DASVT, but no main effect for experience and no interaction effect. Scores on the two tests were not found to have a significant linear correlation. These findings suggest the possibility that different spatial tests may contain gender biased content. For example, there is a possibility that males on average are more familiar with the isometric graphics used the in PSVT:R, and that women on average are more familiar with the sewing patterns used in the DASVT. Both drafting and apparel design have been historically gendered disciplines. These gendered divisions of labor are not natural or permanent, but are constantly being redefined [31].

Spatial tests have traditionally been used to measure "gender differences" in spatial ability. While fairness is thought to be an important factor for standardized tests in education [13], discussions of fairness rarely address spatial tests. Gender is not intrinsically tied to particular artifacts and practices, yet it is always present in them [31]. Thus, spatial tests themselves, though often considered neutral and fair, may contain content that is more familiar to a particular gender group based on patterns of socialization. We do not present these results to suggest that using a test with feminized content is fairer than using one with masculinized content. Instead, our results should cast doubt on the use of any single standardized test of something as heterogeneous as spatial skills to make judgements about a particular group's suitability for a STEM career. Spatial thinking takes many forms and cannot be adequately captured in a single instrument. We should recognize the role of spatial thinking in fields that are not considered part of STEM. Furthermore, as CAD is increasingly used to model complex surfaces or soft goods, spatial tests the focus solely on transformations of rigid objects depicted in isometric views, like the PSVT:R, may be less applicable to CAD education. Our results support a broader understanding of the spatial construct in CAD education and the use of a more diverse set of instruments to assess spatial thinking.

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