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The Effects of a Spatial Thinking Curriculum on Low-Income Sophomore Summer Scholars

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Abstract

In this research paper, we discuss the Sophomore Fast-Forward Program, a summer bridge program designed for students who have unmet summer financial need. The program's primary purpose is to retain students in engineering majors, thus increasing the number of engineers in the workforce. Students in the program take three courses before the beginning of their second year. One of these three courses is the Professional Planning with Spatial Visualization course which implements the Sorby's Developing Spatial Thinking curriculum. This paper addresses the question: What are the effects of the spatial thinking curriculum on the spatial abilities of low-income sophomore summer scholars?

Students take the Purdue Spatial Visualization Test: Visualization of Rotations (PSVT:R) and the Revised Minnesota Paper Form Board Test (RMPFBT) as a pre- and post-assessment for this program. The PSVT:R is traditionally administered as a pre/post assessment of spatial visualization in engineering majors. In this work, it was chosen to assess knowledge gains because Sorby's curriculum includes a strong focus on rotations. The RMPFBT was included as a pre/post assessment because it is a well-established, validated instrument for spatial visualization, and it includes two versions, thus allowing us to control for memory effects.

We compared both tests matched pre-data and post-data to investigate if the implementation of this curriculum improved student's spatial visualization skills. Suitable statistical tests were performed to analyze the data from all six summers. While the students completed the PSVT:R during every implementation of the Sophomore Fast-Forward Program, they did not take the RMPFBT during 2017 (first year of program) or in 2020 (COVID-19 year, virtual program and RMPFBT is a physical assessment). Analysis of RMPFBT instead includes data from four summers.

We found that the PSVT:R scores showed significant improvement with moderate effect sizes. The PSVT:R also showed a significant gender effect with males scoring higher than females. No effects by program year were present. RMPFBT scores showed an overall improvement with no gender effects, although pairwise analysis showed the improvement was concentrated in the 2021 cohort. We conclude that the curriculum is beneficial to include in engineering programs to help students with their three-dimensional spatial ability skills and may additionally benefit two-dimensional spatial ability skills.

Keywords: Spatial Ability, Visualization, PSVT:R, RMPFBT

Introduction and Background

The Sophomore Fast-Forward Engineering Program is a summer bridge and scholarship program at Louisiana Tech University funded by the National Science Foundation that allows rising sophomore engineering students to continue their curriculum ahead of schedule [1]. Eligibility is based on unmet financial need and on-track degree progression to achieve a 4-year graduation. The program allows students to get more interaction with the faculty as well as increased interaction with their peers. The program also allows students to take part in local industry visits so that students may see first-hand various engineering workplace settings. Due to COVID-19, the industry visits were virtual for the Summers of 2020 and 2021. Students participated in Zoom lectures from industry representatives instead of visiting the sites in person. The program was completely online during Summer 2020 due to the COVID-19 pandemic. Fast-Forward students take Calculus III, Statics, and a professional development course that includes a spatial visualization curriculum.

The Professional Planning with Spatial Visualization course involves resume writing, mock interviews, team-building, professional communication, and spatial visualization. The spatial visualization component of the course closely followed the Developing Spatial Thinking program [2] [3] [4] [5] [6] [7]. Developing Spatial Thinking is supported by ENGAGE; a project funded by the National Science Foundation that creates resources for Engineering Faculty to use in order to help their students [8]. The program covers revolutions, hollow objects, overlapping, cutting, joining, intersecting, projecting, and rotations [9]. In the present research, we used two different measures to address the research question: What are the effects of the spatial skills training on the spatial abilities of low-income sophomore summer scholars?

Implementation

Students received spatial skills training (the Developing Spatial Thinking program) that should help them improve their scores on the Purdue Spatial Visualization Test: Visualization of Rotations (PSVT:R). However, students were not taught content aimed at helping them improve their scores on the Revised Minnesota Paper Form Board Test (RMPFBT). The Developing Spatial Thinking content was also taught differently throughout the six years of the program. In the years 2017-2020, the training was integrated into class time where the students watched videos on spatial thinking, with the instructor going over examples of each topic afterwards. In 2021, the students were asked to watch the videos beforehand and class time was reserved for the instructor to go over examples and for students to ask questions. In 2022, no class time was reserved for the spatial skills instruction. Students were told to watch the videos outside of class and ask the instructor any questions they may have during office hours. In this year, students were also assessed through mastery-based grading. Students were given an assignment and received feedback. They were then allowed to complete a similar assignment to receive a better grade. The mastery learning was only implemented in the 2022 summer. Before beginning the Developing Spatial Thinking instruction, participants took the PSVT:R and the RMPFBT. At the conclusion of the program, the scholars took the PSVT:R again and an alternate form of the RMPFBT.

Measurement

The Purdue Spatial Visualization Test includes three subscales: developments, rotations, and views. Each subscale has two possible numbers of items: 30 and 12 [10]. Prior literature indicates that enforcing a time limit can exacerbate a gender performance gap [11]. Our study implemented the thirty-item rotations subscale (PSVT:R). This instrument focuses on measuring an individual's three-dimensional mental rotation ability.

In the second year of the program (2018), the project team introduced a second measure, the Revised Minnesota Paper Form Board Test (RMPFBT) [12]. First published in the 1930's, the test measures an individual's ability to manipulate two-dimensional objects in their mind and is often used to assess spatial visualization skills in engineering students. Unlike the PSVT:R, the RMPFBT has two equivalent forms, which should reduce practice effects. In 2018 and 2021, form AA was given as the pre-test, and BB was given as the post-test. In 2019 and 2022, the forms were reversed (BB as the pre-test). As a paper-and-pencil test, the RMPFBT could not be administered in 2020.

Reliability refers to the stability of test scores over time and the internal consistency of the items to measure the construct of interest. The RMPFBT has been shown to have high reliability, with studies reporting high levels of test-retest reliability and high levels of internal consistency. This means that individuals who take the RMPFBT multiple times are likely to receive similar scores, and that scores on different items within the test are highly correlated. Quasha and Likert report the reliability of a single series (or form) as 0.85 [12]. Evidence of the reliability of the PSVT:R comes from two studies. The first study was conducted with 180 undergraduate education majors enrolled in math classes. Cronbach's alpha of the PSVT:R was reported to be 0.80 [13]. Another study sampled 585 first year engineering undergraduates and reported a Cronbach's alpha of 0.90 [14].

Both instruments have been previously used to measure spatial visualization ability in relation to STEM fields [15] [16] [17] [18]. However, the RMPFBT emphasizes two-dimensional views, while the focus of the PSVT:R is three-dimensional rotations. Overall, the PSVT:R and RMPFBT are considered to be valid and reliable measures of spatial visualization ability and are widely used in educational research settings to assess this important cognitive skill.

Project Data

Due to the NSF-funding requirements, only low-income students were eligible to participate in the program. Therefore, the number of participants was limited. Throughout the six summers of the program, there were a total of 99 participants. However, one person elected to not participate in the research, and thus, their data on all measures was removed from the analysis. Data from an additional student was removed for "speeding" (i.e., completing the PSVT:R post-test in less than five minutes when the standard time limit is 20 minutes to complete 30 questions of increasing difficulty) [19] [20]. A total of 97 participants across six summers were included in the PSVT:R analyses. The RMPFBT was added in 2018 but could not be administered in-person in 2020 due to COVID-19. A total of 68 participants across four summers were included in the RMPFBT analyses.

For NSF-funding tracking, every student was required to complete a demographic survey. In this survey, students choose their gender and that gender is what we used to report whether they were categorized as male or female. For the PSVT:R, 29 participants identified as females and 68 as males. For the RMPFBT, 21 participants identified as females and 48 as males. The racial composition of the participants was 80% White, 14% Black or African American, 3% American Indian or Alaska Native, and 2% Asian. Additionally, 8% reported their ethnicity as Hispanic or Latino. These demographic numbers are not typical of the Louisiana Tech University College of Engineering and Science. Our data sample had a higher percentage number of females (30%) versus the college average of 20.1%. The College of Engineering and Science offers majors in Mechanical, Electrical, Chemical, Industrial, Nanosystems, Civil, Biomedical, and Cyber Engineering. The Fast-Forward program had engineering students from all of the engineering majors. At Louisiana Tech University, all engineering majors take the exact same classes with the exception of Biomedical engineering majors, who take an additional Biomedical specific course in the Spring of their Freshman year. The first year curriculum for engineering majors involve three courses of project-based learning engineering classes, pre-calculus, calculus 1, calculus 2, Physics, and Chemistry courses. Since the majority of the students take the exact same classes, the major of each student will not have an impact on the results. The number of participants and genders of participants for the PSVT:R and RMPFBT can be seen in Table 1.

Table 1: *Program Participants Genders by Year and Test*

	PSVT:R			**RMPFBT**		
Year	Total	Male	Female	Total	Male	Female
2017	18	12 (66%)	6 (33%)	-	-	-
2018	17	13 (76%)	4 (24%)	17	13 (24 %)	4 (24%)
2019	18	10 (56%)	8 (44%)	18	10 (56%)	8 (44%)
2020	11	9 (82%)	2 (18%)	-	-	-
2021	16	10 (63%)	6 (38%)	16	10 (63%)	6 (38%)
2022	17	14 (82%)	3 (18%)	17	14 (82%)	3 (18%)
Total	97	68 (70%)	29 (30%)	68	47 (69%)	21 (31%)

Methods

The following research question was developed to guide analysis:
What are the effects of the spatial thinking instruction on the spatial abilities of low-income sophomore summer scholars?

Specifically, we sought to investigate the following questions:

1. Did PSVT:R/RMPFBT scores improve from pre-test to post-test?
2. Did the effect vary by year?
3. Did the effect vary by gender?

A mixed two-way ANOVA was used to examine the between-subjects effects of year and the within-subjects effects of timepoint (pre/post), followed by Bonferroni-adjusted pairwise comparisons as appropriate for each test. A second mixed two-way ANOVA was used to examine gender effects of each instrument.

Data analysis was carried out using R version 4.2.3 [21] and RStudio [22]. All statistical tests were conducted with the assumption of alpha equals 0.05. The repeated measures ANOVA and the subsequent post hoc tests were completed primarily using the *rstatix* package, version 0.7.2 [23]. Effect size is presented as Cohen's *d* with 95% confidence interval. A common interpretation of Cohen's *d* is small ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$) [24].

Results

Descriptive statistics are summarized by gender and program year in Table 2.

Table 2. *Means and standard deviations for PSVT:R and RMPFBT*

	timepoint					
	pre		post		Change	
	M	*SD*	*M*	*SD*	*M*	*SD*
PSVT:R	**21.37**	**5.16**	**23.42**	**4.51**	**2.05**	**3.44**
Male	22.41	5.31	24.25	4.58	1.84	3.51
Female	18.93	3.91	21.48	3.76	2.55	3.26
2017	21.89	5.17	24.28	3.77	2.39	3.05
2018	22.35	4.8	23.29	5.47	0.94	3.77
2019	20.22	4.43	22.89	3.83	2.67	3.40
2020	19.27	5.78	23.73	4.61	4.45	4.20
2021	21.31	5.69	22.06	5.5	0.75	2.86
2022	22.47	5.43	24.29	4.01	1.82	2.86
RMPFBT	**46.31**	**8.56**	**49.98**	**7.96**	**3.64**	**6.22**
Male	46.33	8.75	49.97	7.61	3.64	5.58
Female	46.26	8.33	50.00	8.89	3.74	7.25
2018	46.09	11.68	48.05	9.99	1.95	5.60
2019	46.72	7.52	49.20	6.28	2.48	6.61
2021	43.02	8.24	50.44	8.83	7.41	5.69
2022	49.16	5.19	52.31	6.31	3.14	5.29

Note. M and *SD* represent mean and standard deviation, respectively.

All correlations between pre- and post-test scores were statistically significant (Table 3). Each instrument showed high correlation between pre and post administrations, 0.73 for the RMPFBT (which used equivalent forms) and 0.78 for the PSVT:R. The two instruments were also related to each other, with correlations of 0.51 and 0.52 at pre and post, respectively.

Table 3. *Correlations with confidence intervals*

Variable	1	2	3
1. RMPFBT_pre			
2. RMPFBT_post	.73** [.60, .83]		
3. PSVT:R_pre	.51** [.31, .67]	.37** [.15, .56]	
4. PSVT:R_post	.61** [.43, .74]	.52** [.32, .67]	.78** [.66, .86]

Note. Values in square brackets indicate the 95% confidence interval for each correlation. * indicates $p < .05$. ** indicates $p < .01$.

Effects by program year

The first two-way mixed ANOVA (Table 4a) shows that the program year had no significant main or interaction effects of PSVT:R scores. The significant main effect of timepoint indicates that after accounting for within-subjects variance, the post-scores were significantly different from the pre-scores. A paired t-test (Table 4b) confirms the significance and shows the post-scores were higher than the pre-scores with a moderate effect size (d = 0.60).

Table 4a. *ANOVA results using PSVT:R as the dependent variable*

Predictor	df_{Num}	df_{Den}	F	p	
year	5	91	0.548	7.39e-01	
timepoint	1	91	39.939	9.52e-09	*
year:timepoint	5	91	2.183	6.30e-02	

Note. Type III sums of squares. df_{Num} indicates degrees of freedom numerator. df_{Den} indicates degrees of freedom denominator. * $p < .05$

Table 4b. *Paired comparison of timepoint main effect (post - pre)*

Dependent Variable	t	df	p	d	95% CI of d
PSVT:R	5.88	96	< .001*	0.60	[0.38, 0.81]

Note. * $p < .05$

The analysis of variance of RMPFBT shows that there is a significant interaction between year and timepoint, as well as a significant main effect of timepoint (Table 5a). The interaction indicates that the effect of timepoint (change in score from pre to post) was not consistent in all years. Individual paired t-tests within each year (Table 5b) show that 2021 was the only year that the change was significant based on Bonferroni adjusted p-values. In that year, there was also a large effect size of $d = 1.30$.

Table 5a. *ANOVA results using RMPFBT as the dependent variable*

Predictor	df_{Num}	df_{Den}	F	p	
year	3	64	0.936	4.29E-01	
timepoint	1	64	27.993	1.58E-06	*
year:timepoint	3	64	2.983	3.80E-02	*

Note. Type III sums of squares. df_{Num} indicates degrees of freedom numerator. df_{Den} indicates degrees of freedom denominator. * indicates $p < .05$

Table 5b. *Effect of timepoint (post - pre) within year*

year	t	df	p	d	95% CI of d
2018	1.44	16	.679	0.35	[-0.15, 0.83]
2019	1.59	17	.521	0.37	[-0.11, 0.85]
2021	5.21	15	< .001	1.30	[0.62, 1.96]
2022	2.45	16	.105	0.59	[0.07, 1.10]

Note. p values are adjusted using the Bonferroni correction. CI indicates confidence interval. *d* indicates Cohen's *d.*

Effects by gender

To examine the effects on spatial abilities by gender, we used a 2 x 2 ANOVA, again with a within-subject repeated measure (Table 6a). The non-significant interaction effect indicates that males and females had similar changes in score from pre to post. The PSVT:R showed significant main effects of timepoint and gender. Participants' post-test scores were significantly higher than their pre-test scores (see table 4b), and overall, males' scores were higher than females' scores (Table 6b).

Table 6a. *ANOVA results by gender using PSVT:R as the dependent variable*

Predictor	df_{Num}	df_{Den}	F	p	
Gender	1	95	10.61	2.00E-03	*
timepoint	1	95	33.162	1.04E-07	*
Gender:timepoint	1	95	0.876	3.52E-01	

Note. Type III sums of squares. df_{Num} indicates degrees of freedom numerator. df_{Den} indicates degrees of freedom denominator. * $p < .05$

Table 6b. *Pairwise comparisons of gender main effect (male-female)*

Dependent Variable	t	df	p	d	95% CI of d
PSVT:R	4.59	133.49	< .001	0.66	[0.34, 0.97]

Note. CI indicates confidence interval. *d* indicates Cohen's *d.*

The RMPFBT did not show any gender effects or interaction, only a main effect of timepoint, which the previous section showed was largely driven by the 2021 cohort (Table 7).

Table 7a. *ANOVA results by gender using RMPFBT as the dependent variable*

Predictor	df_{Num}	df_{Den}	*F*	*p*	
Gender	1	66	0.0001	9.92E-01	
timepoint	1	66	21.05	2.06E-05	*
Gender:timepoint	1	66	0.004	9.51E-01	

Note. Type III sums of squares. df_{Num} indicates degrees of freedom numerator. df_{Den} indicates degrees of freedom denominator. * indicates $p < .05$

Figures 1 and 2 illustrate the findings by gender. Both instruments demonstrated significant main effects with regard to timepoint, which is represented by the changes from pre-to post. The slopes are nearly parallel within each figure which is indicative that there were not significant interactions. Finally, we see that while males and females scored nearly the same on the RMPFBT, the males scored consistently higher than the females on the PSVT:R.

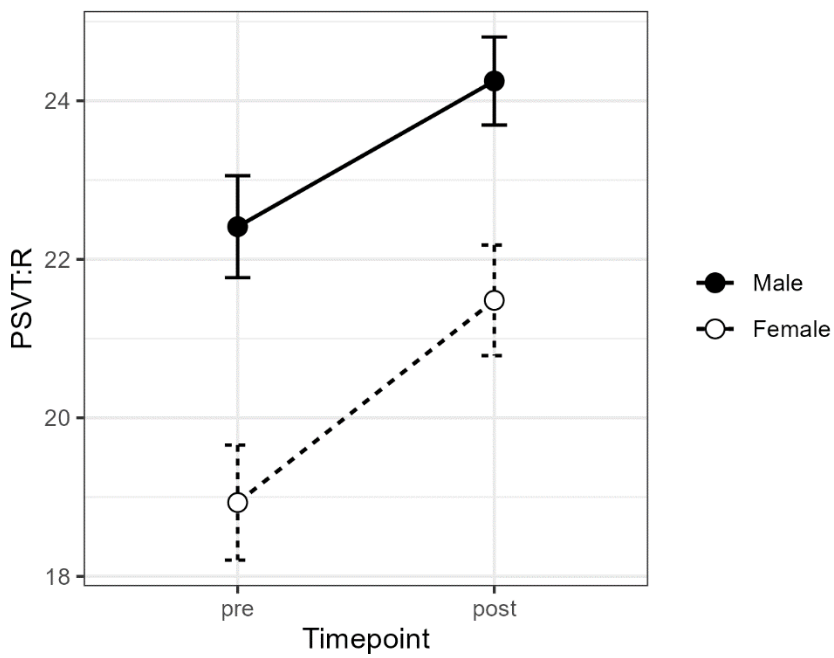

Figure 1: PSVT:R Scores across time points by gender

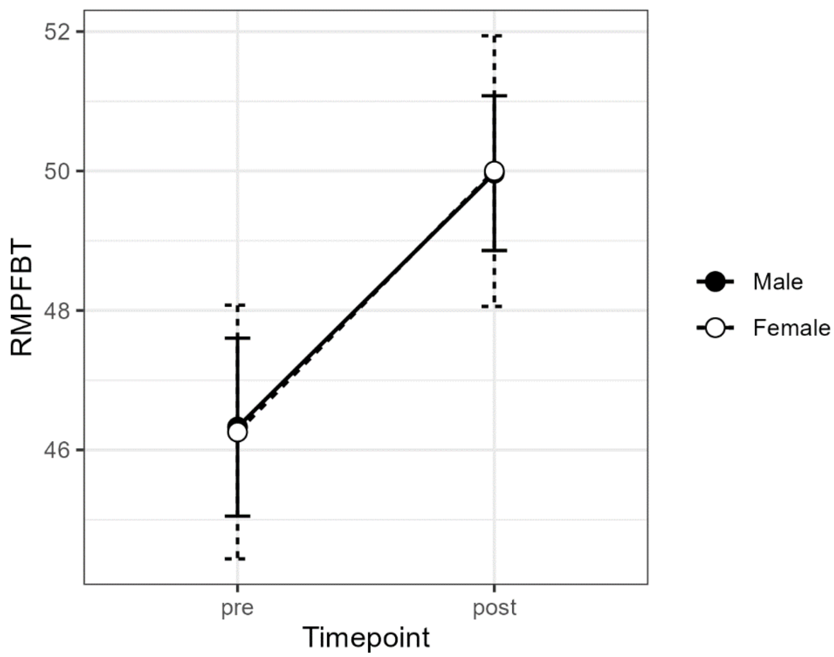

Figure 2: RMPFBT Scores across time points by gender

Discussion

Both PSVT:R and RMPFBT scores increased from pre-test to post-test when examined overall. These results indicate the spatial skills training had an impact on students' spatial visualization performance on these measures. This finding is interesting because the spatial skills training focused on three-dimensional visualizations, especially rotations, while the RMPFBT is an assessment based on two-dimensional visualizations. Therefore, including the spatial skills training in an engineering curriculum could potentially help students with both two- and three-dimensional visualizations.

Interestingly, despite three models of implementation of the spatial visualization curriculum over the course of the project (See Implementation section), the program year had no significant effects on the PSVT:R scores. The PSVT:R post-test scores were significantly different from the PSVT:R pre-test scores for all years. However, there was a significant interaction between years for the RMPFBT. The interaction shows that the change in score from the pre-to post was not consistent in all years. The change in 2021 was significant for the RMPFBT scores. As described in the Implementation section, there was no direct instruction toward the spatial visualization skills tested in the RMPFBT. Therefore, it is not surprising to find only one year where there was a significant effect. In the year 2021, the change was significant between pre and post test. During 2021, the spatial skills training was implemented with a flipped classroom format. Students were asked to watch the videos beforehand and were allowed to ask the instructor any questions they had about the material during class. However, as noted before, the spatial skills training focused on three-dimensional visualizations and not two-dimensional visualizations as tested by the RMPFBT. Further, this difference could be due to the fact that students were more engaged after coming back from online classes.

Turning to the comparison between males and females, the PSVT:R showed a significant main effect of gender, while the RMPFBT did not. PSVT:R scores were higher for males than females. On the magnitude of the change from pre- to post-test, there was not a significant difference between males and females on the PSVT:R nor the RMPFBT measures. The PSVT:R results are consistent with the numerous studies that have identified spatial ability differences by gender, in favor of males [11] [16]. The gender difference may be due to the PSVT:R focusing on more complex 3D spatial visualization while the RMPFBT is two-dimensional [11] [10]. Neither test showed a significant interaction between gender and timepoint, which suggests that the training did not have differential effects by gender. Although males started with higher PSVT:R scores, males and females made approximately the same gains. One possible explanation for this is that the instruction may have had little impact on the most gender-biased PSVT:R items. This could be further explored with an item analysis to see if participants were more likely to improve on some PSVT:R items than others.

Conclusions

Students consistently showed improvement on two spatial ability measures: PSVT:R and the RMPFBT over the twelve-week Fast-Forward program, which included the Developing Spatial Thinking training. Although the PSVT:R showed gender differences with males outscoring females, males and females showed similar improvement. Explicit instruction in spatial thinking was beneficial to both male and female participants, despite the groups starting at different levels on the three-dimensional PSVT:R. Therefore, the curriculum is beneficial to include in engineering programs to help students with their three-dimensional spatial ability skills.

Even though the instruction was developed with the three-dimensional PSVT:R in mind, benefits were also seen in RMPFBT scores overall, with only one year (2021) reaching statistical significance on its own. This difference could be due to the different implementation of the curriculum or could be due to the fact that students were more engaged after coming back from online classes. Since there were no significant effects on the PSVT:R by year, the different implementation types did not affect how the students performed on the PSVT:R assessment. These findings confirm that both groups benefited from the training and that the effects were not limited to the specific instrument used in the training design.

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