Longitudinal analysis of spatial ability over an undergraduate engineering degree program

Dr. Maxine Fontaine, Stevens Institute of Technology (School of Engineering and Science)

Maxine Fontaine is a Teaching Assistant Professor in Mechanical Engineering at Stevens Institute of Technology. She received her Ph.D. in 2010 from Aalborg University in Aalborg, Denmark. Maxine has a background in the biomechanics of human movement, and she currently teaches several undergraduate courses in engineering mechanics. Her research interests are focused on improving engineering pedagogy and increasing diversity in engineering.

Dr. Alexander John De Rosa, Stevens Institute of Technology (School of Engineering and Science)

Alexander De Rosa is a Teaching Assistant Professor in Mechanical Engineering at Stevens Institute of Technology. Alex specializes in teaching in the thermal-fluid sciences and has a background in experimental combustion. He gained his PhD in 2015 from The Pennsylvania State University in this area.

Longitudinal analysis of spatial ability over an undergraduate engineering degree program

Abstract

This research paper will compare the spatial ability of students in their first year and final year to determine whether spatial skills improve over the course of an undergraduate engineering degree program. In addition, we investigate whether higher spatial ability leads to a higher overall GPA at the time of graduation. This work was initiated with support from NSF Grant #0833076.

Spatial ability has been identified as a key indicator of success in STEM. Thus, students with low spatial visualization skills (SVS) are more likely to drop out of an engineering program. Spatial skills can however be improved significantly with focused practice. A spatial skills assessment and training program has been implemented at Stevens Institute of Technology since 2016 and has been shown to be effective; pre- and post-training, average test scores on the Purdue Spatial Visualization Test: Rotations (PSVT:R), a measure of spatial ability, increased from 54.4% to 68.7% in fall 2017 (n=42), and from 55.2% to 68.7% in fall 2018 (n=51).

Data collected over the past several years in our spatial skills program allows us to examine whether these immediate gains in spatial ability are retained over the course of a students' education or whether they require practice to be maintained. This study aims to examine both the longitudinal retention of SVS and potential improvements over the course of the engineering degree program.

To address these questions, the PSVT:R scores of graduating (senior) engineering students were compared with their PSVT:R scores from their first year. Of the students involved in this study, 102 of 120 participants retained the same level of SVS from first to final year (79% passed the PSVT:R both times, 6% failed both times), while 15% of students shifted from one category to the other (8% initially passed then failed, 7% initially failed then passed). Significant improvements in test score were only observed between pre- and post-test scores for first-year students who participated in the spatial skills training workshop. No difference in these results was observed when students were grouped by gender and no significant link between SVS ability and graduating GPA was observed.

Given prior results in this area, the lack of correlation between SVS and GPA was surprising, as was the observed lack of development in SVS through the program. It is possible however that many classes at Stevens do not rely heavily on these skills or that students can make up for them in other ways, e.g. teamwork. Future work will address these questions.

Introduction

Spatial-visualization skills (SVS) are known to be critically important to success and retention in STEM fields. At the same time, these skills are often learned through life experiences such as playing sports, or playing with certain toys, rather than being taught explicitly in a formal setting [1-4]. Due to this reliance on life experience, the levels of spatial skills displayed by women and underrepresented groups are typically lower than that of other student populations. Importantly however, spatial skills can be learned and improved with appropriate training.

One of the most widely known SVS enhancement programs, "Developing Spatial Thinking", was introduced by Sheryl Sorby [5,6]. The suggested curriculum consists of ten, 1.5 hour lab sessions that are usually delivered in an extra-curricular setting and feature both software and workbook exercises. This curriculum, as well as others based on it have since been adopted by over 40 institutions working with the NSF Engage initiative [7]. Several other programs have also been developed while more recent efforts to aid in teaching SVS include the usage of games and smartphone apps for this purpose.

Across all of these settings, spatial skills assessment and training programs have been shown to be effective in improving student retention, particularly amongst women [8,9], as well as to have positive impacts on the persistence of students within a program. Students who receive SVS training are more likely to stay in their major rather than transfer to another discipline. Additionally, several studies have shown the positive impacts that high levels of SVS, and SVS training, have on follow-on courses by examining differences in GPAs between groups of differing spatial ability [8].

While the positive impacts of examining spatial skills and offering remediation for those who do not meet a threshold of ability have been strongly evidenced, few studies have examined the retention of the spatial skills themselves over the course of a degree program or the extent to which SVS training and ability affects overall success in the major of the student. In this study, we aim to address this gap by investigating, and comparing, the spatial ability of both first-year engineering students and graduating seniors. As our spatial skills program was implemented in 2016, a sizeable population of students who were assessed and trained in spatial skills as incoming students are now graduating and the evolution and impacts of their SVS through their college career can be studied.

Methodology

All first-year engineering students at Stevens Institute of Technology are enrolled in a graphics class in which their spatial skills are initially assessed before students are given the option to partake in voluntary (incentivized), extra-curricular spatial skills training workshops. The spatial ability of the students is tested using the Purdue Spatial Visualization Test: Rotations (PSVT:R) [10], with a passing grade set at 70%. Training workshops are based on the CU Boulder format described by Segil et al. [11]. The program at Stevens was initially implemented in 2016, and over 1600 first-year engineering students have benefitted from its introduction to date. Approximately 15% of these students have benefitted directly from the spatial skills intervention. Further details of the spatial skills assessment and training program at Stevens can be found in prior work [12,13].

In order to assess the development of spatial skills over the course of the program, all graduating engineering students were requested to voluntarily complete the PSVT:R spatial skills assessment in their final year. In order to incentivize participation, the assessment was offered as an extra credit assignment in their senior design (capstone) course.

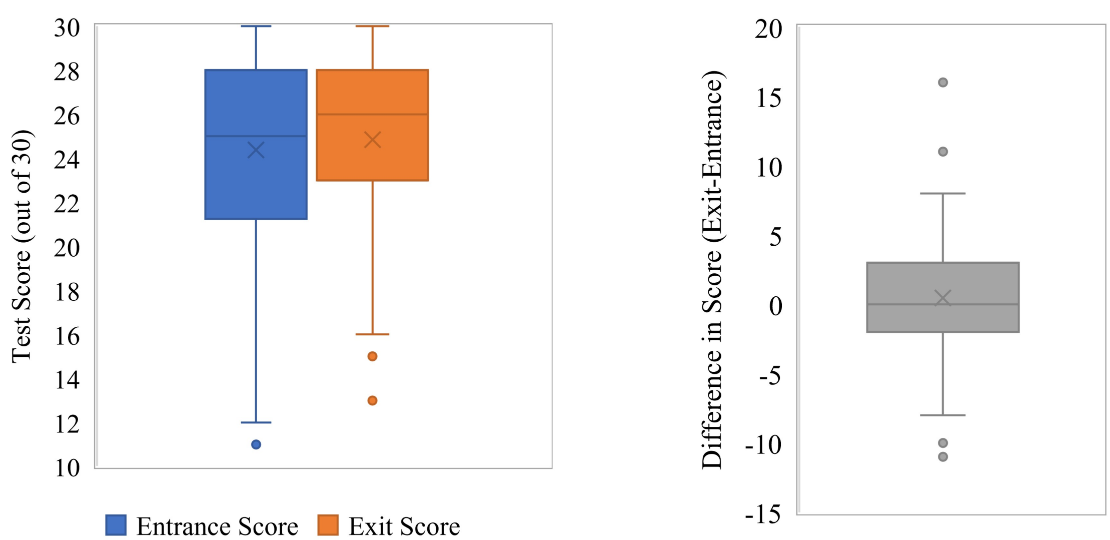
In this study, the PSVT:R taken in the first year is referred to as the entrance exam, while the PSVT:R taken in the final year is referred to as the exit exam.

Results

A total of 120 graduating engineering students (74 male, 46 female) from a variety of majors (61 Mechanical, 42 Civil, 18 Other) participated in this study. Scores on the entrance exam (M = 24.38, SD = 4.01) and exit exam (M = 24.84, SD = 3.89) are compared in Figure 1a. Differences are not significant, $t(119) = -1.248$, $p = .214$, although mean and median test scores in the final year were slightly higher than those in the first year, indicating a slight improvement in spatial ability overall.

Individual differences in score from first year to final year, shown in Figure 1b, are also indicative of a similar trend. The mean difference is slightly positive, showing an overall gain of +0.42 points. Figure 2 also demonstrates that overall pass rates among the students are comparable, although the overall pass rate actually decreased slightly from first year to final year (87.5% vs. 85.8%). A test score of 70% and above (21+ out of 30) is considered a passing grade.

Figures 1 and 2, show how the average test score increased slightly while the overall pass rate decreased slightly from first year to final year. A closer look at the distribution of test scores (Fig.3) explains this seemingly contradictory result. Figure 3 shows a large number of students passed with a score in the 21-23 range in their first year, while a large number of students scored in the 24-30 range in their final year. This result leads to a higher average test score in the final year, despite the greater number of students who failed the test in the final year.



(a) First and final year test scores

(b) Difference in entrance/exit scores

Figure 1. Box plots of test scores, taken in the first year and final year of an engineering degree program.

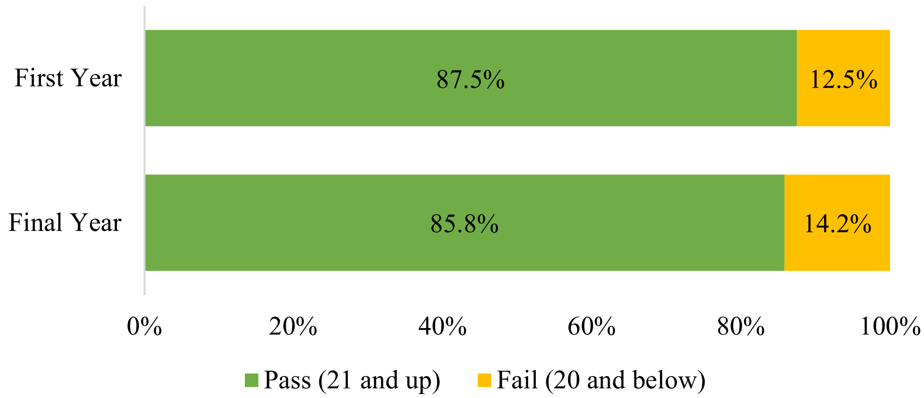


Figure 2. Overall pass rates for entrance and exit exams (n=120).

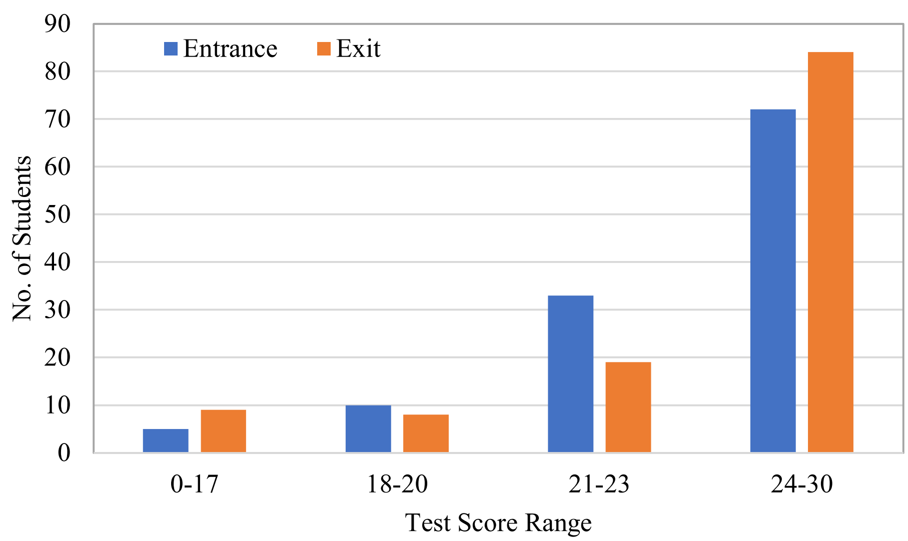


Figure 3. Distribution of test scores for engineering students in their first year vs final year.

Student performance on the entrance and exit exams is broken down in Table 1. Of the 105 students who initially passed the test in their first year, 95 of these students passed the test again, while 10 of these students failed the test in their final year. Of the 15 students who initially failed the test in their first year, 7 of these students failed the test again, while 8 of these students passed the test in their final year.

Table 1. Progression of exam scores from first year to final year.

		Exit Exam Score:	
Entrance Exam Score:	*Count:*	**0-20**	**21-30**
0-20	15	7	8
21-30	105	10	95
	Count:	17	103

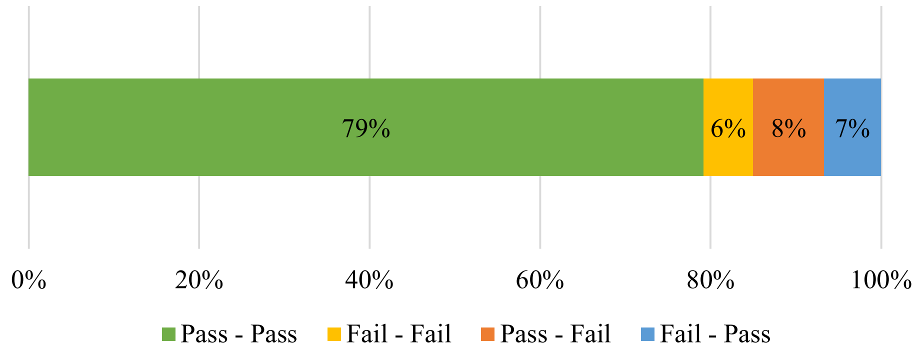


Figure 5. Changes in exam score from first year to final year.

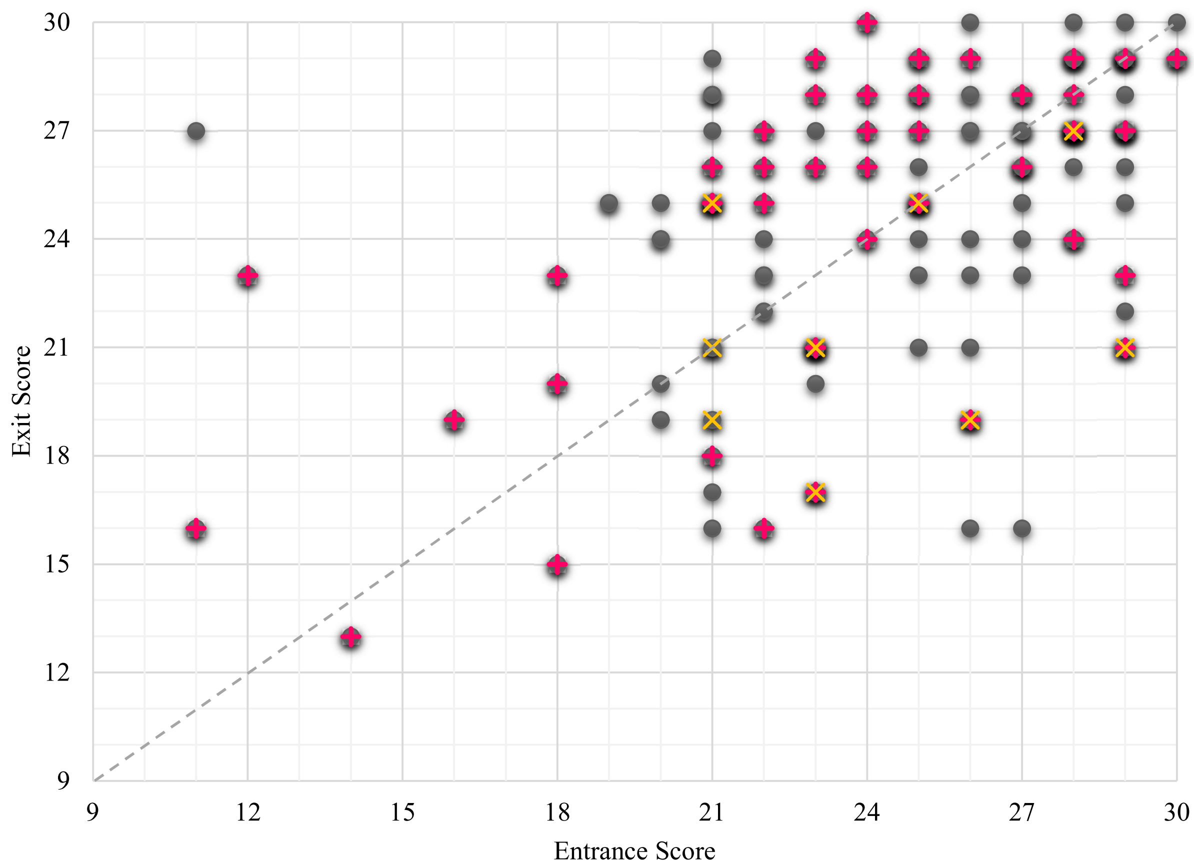


Figure 6. Exit exam scores vs. entrance exam scores for all engineering students (n=120). Larger dots indicate multiple students at the same data point. Female students data points (n=46) indicated with a cross (+) marker, and workshop participant data points (n=9) indicated with an 'x' marker.

Figure 5 shows that the majority of students (102 of 120 = 85%) remained in the same category from first year to final year (79% passed both times, 6% failed both times), while 15% of all students shifted from one category to the other (8% initially passed then failed, 7% initially failed then passed).

A graphical representation of student performance on the entrance and exit exams is detailed in Figure 6. Of the 7 students who failed the test both times, 5 of these were female. This result is unsurprising given that women are typically found to have lower spatial ability than men and that similar results have been observed in the literature.

It should be noted that data points with differences of 10 or more in entrance vs exit score could be unreliable. These include 2 out of 72 students who initially passed with scores of 24 and above that then failed the exit exam with scores of 16 (see Figure 6). A decrease in spatial ability of this magnitude is unlikely and can probably be attributed to a lack of effort on the exit exam due to a lack of proper incentive. More interesting are the two students who initially scored below 13 but scored above 22 on the exit exam. It is possible that these students did not put forth their best effort in the first year test but it could also be the case that their scores improved as a result of an increase in their spatial ability through the engineering program.

The results detailed here seem to indicate that for most engineering students, spatial ability remains constant throughout the program. Significant changes were only seen for a small subset of the survey population. It is possible that spatial skills atrophy over time if they are not used, a result that might be expected for students entering the program with lower spatial ability. It is also possible however, that students who are exposed to further situations in which they are required to use spatial skills would improve their aptitude. While prior work in the literature has examined areas in which spatial skills are important in an engineering program, it remains to be seen which courses and activities at Stevens could be listed as those that specifically employ them.

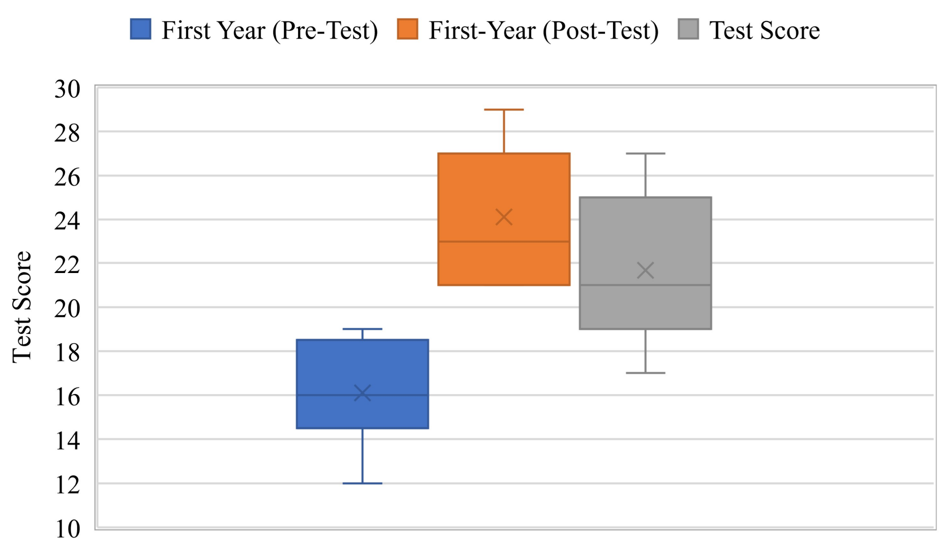


Figure 7. Box plots comparing first-year pre-test scores, first-year post-test scores, and final year test scores for workshop participants (n=9).

Of the total 120 students, only 9 students (6 female, 3 male) participated in the spatial skills training workshop in their first year, so only a limited comparison of participants and non-participants in the workshop can be performed here. Details of their test scores are shown in Figure 6. Figure 7 shows first-year pre-test scores (M = 16.11, SD = 2.23), first-year post-test scores (M = 24.11, SD = 2.88), and final year test scores (M = 21.67, SD = 3.13). A significant improvement is observed between pre- and post- test scores, $t(9) = -8.113$, $p = .000$, following the training workshop. Although the average test score decreases from post-workshop to the final year, this difference is not significant, $t(9)=1.892$, $p = .095$The increase between pre-test and final year test score does however remain significant, $t(9)=-4.490$, $p = .002$, indicating that the gains in spatial ability following the training workshop are retained to some extent over the course of the engineering degree program.

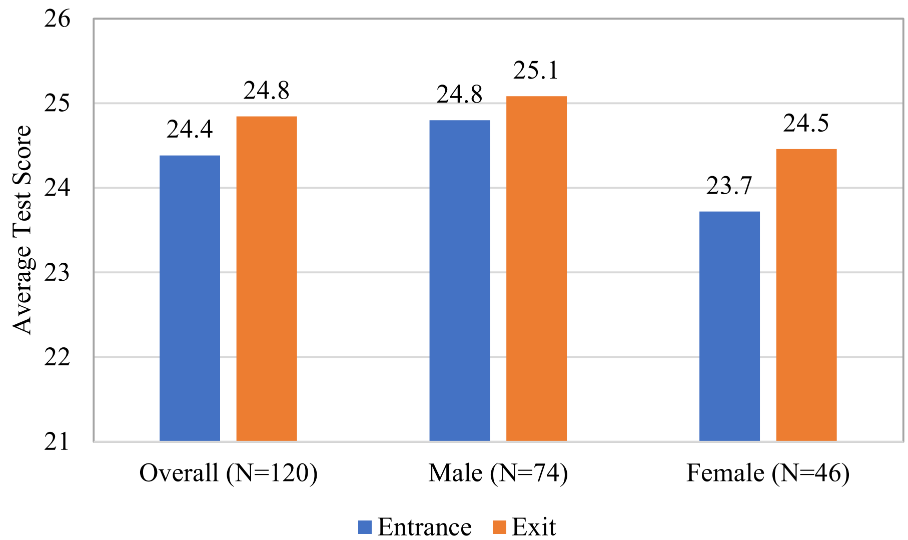


Figure 8. Gender differences in average test scores (out of 30) in first year and final year of an engineering degree program.

In order to further examine possible differences in spatial ability between men and women, entrance and exit test scores, split by gender, are plotted in Figure 8. The differences in spatial ability are more pronounced in the entrance exam scores, where the average test scores for first-year males and females are 24.8 and 23.7, respectively. By the time of graduation, the gap has narrowed slightly, such that average test scores for graduating male and female engineering students are 25.1 and 24.5, respectively. Gender differences in entrance exam scores ($F(1,118)=2.055$, $p=0.154$) and in exit exam scores ($F(1,118)=0.724$, $p=0.396$) were not found to be statistically significant. It is interesting however that women still lag behind their male colleagues in measures of spatial ability, a result that is also commonly observed in the literature.

In order to examine the impact of spatial skills on success in the course of their studies, the cumulative GPA of the graduating students (n=120) is compared with their exit test scores in Figure 9. There is no observable correlation between spatial ability and success as measured by these metrics ($R^2 = 0.0052$). It is possible that GPA is not a good indicator of success in this context or that success in our program is not directly correlated to spatial ability. Given the literature in this field however, the latter explanation seems unlikely.

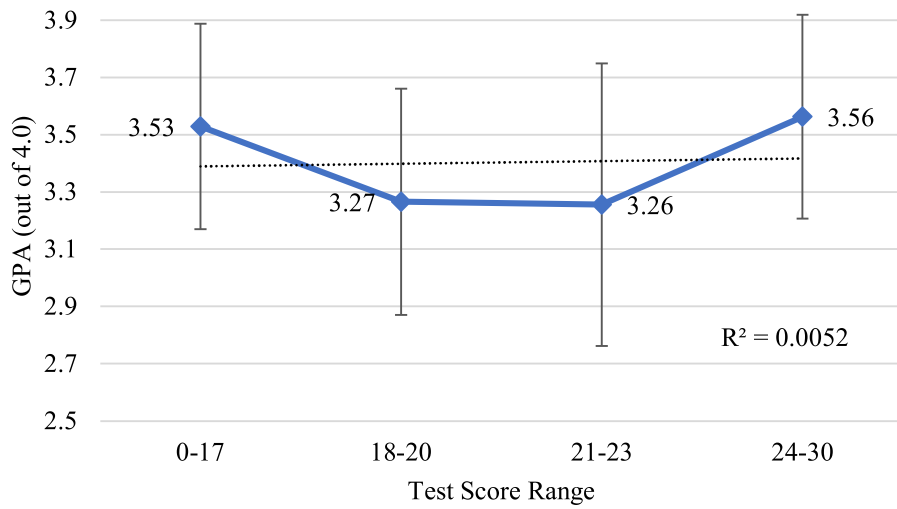


Figure 9. Comparison of success in the program (exit GPA) vs. spatial ability (exit test score).

Discussion

No significant differences were observed between the spatial ability of engineering students in their first year vs. final year, as measured by the PSVT:R. Students who enter with low spatial ability (6% of graduating engineering students) generally maintain a low spatial ability, but are able to successfully complete an engineering program with little effect on overall GPA. Students entering with higher spatial ability (79% of graduating engineering students) maintain a high level of spatial ability and graduate with only a slightly higher overall GPA than their counterparts with low spatial ability.

Given past work in this area [1,3,9], it would appear that either the curriculum at Stevens is not as reliant on spatial skills in order to be successful, or that students are able to work around any deficiencies in these skills that they might experience. As the design courses at Stevens, an arena where students are most likely to need greater levels of SVS, are almost exclusively based around teamwork and group projects, students with lower levels of spatial ability may be aided by their group for example.

As discussed in previous work [12,13], significant differences were observed between pre- and post-test scores of first-year students who participated in a spatial skills training workshop. No significant differences were observed between test scores in the first year (post-workshop) and final year for these workshop participants, indicating that these gains in spatial ability were retained. From the end of their first year to their final year, workshop participants and non-participants alike generally maintained the same level of spatial ability.

No significant differences in spatial ability were observed between female and male engineering students, although the mean test score for females was slightly lower than for males. It should be noted that this study only included engineering students in their final year, who have almost completed the engineering program.

Since the exit exam was voluntary for engineering students in their final year, it is possible that the data may be slightly biased towards students who have better spatial ability. It is also possible that some final test scores may not accurately represent the spatial ability of some students who did not put forth their best effort due to a lack of proper incentive.

Conclusion

The impact of spatial ability on success and persistence in engineering programs, particularly within the first year, has been widely documented in the literature. The retention and potential improvement in spatial ability over the course of an engineering program is less well understood however. In order to address this gap, the spatial ability of students as they entered an engineering program was compared to their ability as graduating seniors. Spatial ability was tested using the Purdue Spatial Visualization Test: Rotations (PSVT:R) and the survey population consisted of 120 graduating seniors in various engineering disciplines.

A primary observation of this study was that the majority of students (102 of 120 = 85%) remained at the same level of spatial ability from first year to final year (79% passed the PSVT:R both times, 6% failed both times), while 15% of all students shifted from one category to the other (8% initially passed then failed, 7% initially failed then passed). Significant improvements in test score were only observed between pre- and post-test scores for first-year students who participated in the spatial skills training workshop. Thereafter, spatial ability for the workshop participants also remained at the same level, indicating the gains in spatial skills were retained. While women initially displayed lower levels of spatial ability than men (as expected), there was no significant differences in either growth in spatial ability through the program or overall success when broken down by gender. In terms of success as an engineering student, no obvious correlation between cumulative GPA and spatial ability as measured by the PSVT:R was observed. There were a few students who experienced significant positive (n=2) and negative (n=2) changes in their spatial ability over the course of their degree. Given the very small sample size of four however, it is difficult to explain these findings.

It should be noted that data presented here are early results from a relatively small sample size of 120 students, and conclusions drawn may have limited validity. We will be able to make stronger conclusive remarks as we continue this longitudinal study over the next several years.

Future Work

Future work will attempt to correlate spatial skills with various activities conducted by the student within their course of study in order to determine at which points these skills are important to their academic success. Work will also be conducted to quantify results based on a different metric for “success” in an engineering program than GPA, such as grades in specific courses.

Acknowledgements

This work was conducted under IRB 2017-011(N) and grew out of work started under the NSF Engage Project, Award #0833076, at Stevens Institute of Technology.

References

[1] Sorby, S., "Educational Research in Developing 3-D Spatial Skills for Engineering Students," *International Journal of Science Education*, vol. 31, no. 3, 2009, pp. 459-480.

[2] Norman, K.L., Spatial visualization – A gateway to computer-based technology. *Journal of Special Educational Technology*, XII(3), 1994, pp. 195–206.

[3] Smith, I.M., *Spatial ability - Its educational and social significance*. London: University of London, 1964.

[4] Wai, J., Lubinski, D., and Benbow, C.P., "Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance," *Journal of Educational Psychology*, vol. 101, no. 4, 2009, pp. 817-835.

[5] Sorby, S., *Developing spatial thinking*, Higher Education Services, 2016.

[6] Sorby, S., and Wysocki, A.F., *Introduction to 3D Spatial Visualization: An Active Approach*. New York, NY: Thomson Delmar Learning, 2003.

[7] "Spatial Visualization Skills (SVS): Learn More," ENGAGE Engineering. [Online]. Available: https://www.engageengineering.org/spatial/whyitworks/learnmore. [Accessed: Jan. 27, 2020].

[8] Sorby, S.A., & Baartmans, B.J., The development and assessment of a course for enhancing the 3D spatial visualization skills of first year engineering students. *Journal of Engineering Education*, (89)3, 2000, 301–7.

[9] Metz, S. and Sorby, S., "Implementing ENGAGE strategies to improve retention: focus on spatial skills engineering schools discuss successes and challenges." ASEE Annual Conference and Exposition, Conference Proceedings. 2011.

[10] Guay, R.B., *Purdue Spatial Visualization Test: Rotations*. West Lafayette, In: Purdue Research Foundation, 1976.

[11] Segil, J., Myers, B., Sullivan, J. and Reamon, D., "Efficacy of various spatial visualization implementation approaches in a first-year engineering projects course," in 2015 ASEE Annual Conference & Exposition, Seattle, Washington, USA, 2015.

[12] De Rosa, A. J., & Fontaine, M., "Implementation and First-Year Results of an Engineering Spatial Skills Enhancement Program." Paper presented at 2018 Mid Atlantic Section Fall Meeting, Brooklyn Technical High School, Brooklyn, New York, New York, 2018.

[13] Fontaine, M., De Rosa, A. J., & Metz, S. S., "A First-Year Engineering Spatial Skills Workshop: Implementation, Effectiveness, and Gender Differences." Paper presented at 2019 CoNECD - The Collaborative Network for Engineering and Computing Diversity , Crystal City, Virginia, 2019.