Teaching Spatial Visualization: A Controlled Trial of a Touchscreen App Implemented as Homework

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***Abstract*— This Research to Practice work-in-progress paper examines the impact of eGrove Education's Spatial Vis touchscreen application for teaching spatial visualization. Research has shown that competency with spatial visualization is correlated with success in engineering, but few engineering programs explicitly teach this skill. In this paper, we describe a controlled trial (n=55) in which the app was assigned as homework for the experimental group, but no additional lecture time was dedicated to spatial visualization training. Our analysis focuses on students who entered the course with limited spatial visualization experience as identified based on a score of ≤70% on the PSVT:R (a reliable, well-validated instrument). Among these low-performing students, those who used the app showed remarkable progress – 8 of 13 (62%) raised their test scores above 70% compared to just 2 of 14 (14%) in the control group. Students in both the experimental and control groups showed statistically significant increases between the pre- and post-test scores (paired t-test), though the difference in the gains between the two groups was statistically insignificant as the study was underpowered. While larger trials will be needed, this work suggests that the Spatial Vis app is a promising intervention for training spatial visualization skills.**

Keywords— Spatial Visualization, Engineering Graphics, First-Year Programs, First-Year Design

I. Introduction

Spatial visualization (SV) refers to the ability to manipulate geometric shapes in one's mind and is important in many STEM fields [1], [2]. A seminal study by Sorby [3] showed that SV skills are learnable, and a single course using freehand sketching on paper has been demonstrated to improve SV skills. Sorby showed that sketching was an important part of increasing 3D visualization skills, and that removal of sketching decreased the benefit of the course. A summary of her work at Michigan Tech [4] covers the period from 1993 to 2012 with over 7,000 students and shows how graduation rates in engineering have significantly increased due to SV training. In the early years of the study, SV training was recommended but not required for incoming students with low SV skills. Accordingly, the students who took the elective SV training course may have been more highly motivated, and some of the correlation with improved graduation rates may have been due to a self-selection bias. However, in the later years of the study, the SV course became required, and with self-selection bias removed the benefits of SV training remained. As a part of her work, Sorby showed SV training is especially beneficial for women and other underrepresented minorities in STEM [5]. Based in part on this evidence, the National Science Foundation funded a program called "Engaging Students in Engineering" or ENGAGE which endorsed adding SV training to STEM curriculum and provided faculty with tools to make this change [6]. Unfortunately, even with this clear evidence, relatively few engineering programs have made substantive changes to their curriculum to explicitly include training in this area. We believe the major hurdle is the fact that engineering curricula are notoriously full, for anything added something else must be taken away. For many programs finding space for a class on SV, or even just a few weeks within an existing course, is not a feasible solution. To this end in this study we had students complete assignments within the app as homework to see if SV training could occur outside of the classroom.

The Spatial Vis app was developed by eGrove Education [7] specifically to make SV training more engaging and easier to teach. The app consists of freehand sketching assignments on a touchscreen, which is motivated by Sorby's finding that the "importance of sketching in developing 3-D spatial skills cannot be understated" [3]. In addition, sketching skills has benefits beyond SV, and has been correlated to communication, teamwork, and creativity [8]. The app runs on iOS and Android devices. Students freehand sketch isometric and orthographic assignments which are automatically graded. If a student's sketch is incorrect, they can try again or get a hint. If they are still stuck, they can peek at the solution. Prior studies with the Spatial Vis app have demonstrated its effectiveness [9]–[11]. In studies [9] and [10] the students worked on the app during the scheduled classroom time. In study [11] students checked out iPads in blocks of 3 hours to complete the assignments as homework.

A unique aspect of the study described herein, is that the university assigned an iPad to each student that they kept for the complete semester, providing students with flexibility as to when and where they performed the assignments. The Spatial Vis app was implemented as homework, and class lecture time of existing curriculum was not reduced. Students who needed more time to complete their sketching assignments could do so at their convenience. Another unique aspect of this study as compared to previous work is the use of a control; one class (the experimental group) used the app while a second class (the control group) did not use the app. Within the experimental group use of the app was required for all students, so there was no self-selection bias in the results.

II. METHODOLOGY

A. Research Questions and Approach

Our work in this study was guided by the research question “Can the Spatial Vis app, when assigned primarily as homework, improve students’ spatial visualization skills?” To measure student’s spatial visualization skills, following the work of Sorby and others [3], [12]–[16], we used the Revised Purdue Spatial Visualization Test: Rotations (PSVT:R) [14], [17]. The PSVT:R is a timed, twenty minute assessment consisting of thirty multiple choice questions of three-dimensional rotation tasks (see Figure 1). We administered this assessment in a pre/post format to measure student change during the course of the semester. Maeda has performed detailed analyses on the reliability for the PSVT:R and found a Cronbach’s $\alpha = .84$ [13], concluding the instrument measures a “unidimensional subcomponent of spatial ability and the scores are reliable for measuring spatial visualization ability of [first year engineering] students [14].” Average scores on this test have been measured to be 71% for females and 82% for males among a sample of US first year engineering students [18]. The item difficulty of the questions in the PSVT:R are high enough that they allow researchers to distinguish STEM student’s mental rotation ability [15], [16].

Of specific interest for this study are students who entered the course with low pre-test scores. A key objective of SV training is to increase graduation rates in STEM. Sorby [4] showed that graduation rates within engineering were higher for those who scored above 70% on the PSVT:R pre-test, yet that those that participated in SV training could bring their graduation rates up substantially. These Sorby studies required SV training for students with pre-test scores below 60%, yet these same studies showed that this group leap-frogged students in graduation rates with pre-test scores between 60% and 70%. This implies that all students with pre-test scores below 70% would benefit from SV training. Other recent spatial visualization studies have also used the 70% threshold as an indicator for a need for SV training [12]. Accordingly, in this analysis we focus on student's whose pre-test was $\leq$70% as they likely have the most to gain from this training.

For students with low pre-test scores, simply looking at average gains in PSVT:R scores does not tell the complete story. Prior studies have shown that student gains can be far from a normal distribution [9]. In this work Delson showed for students with a low pre-test score ($\leq$ 70%), there was a bimodal distribution in PSVT:R gains. One subgroup had significant average gains of 43% (σ=9.7%), while the other subgroup had minimal gains of -4% (σ=9.8%). The difference in these two groups was correlated to students' persistence in using the app, which was measured by how often a student retried an assignment before asking for a hint or a peek at the solution. When the Spatial Vis app was improved to encourage persistence, the number of students with significant improvement almost doubled [10]. Accordingly, a key challenge in SV training is to engage students, and one way to characterize the effectiveness of SV training is by the percentage of student with low pre-test scores who have significant gains on the post-test PSVT:R.

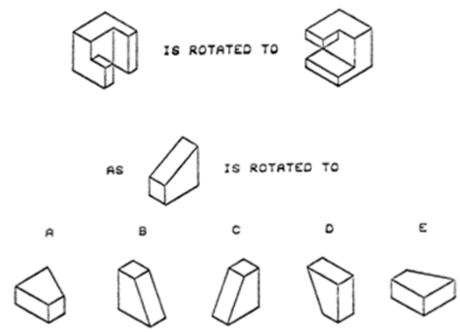

Fig. 1. The Purdue Spatial Visualization Test: Rotations (PSVT:R) sample test assignment [17].

A question remains as to what an appropriate threshold is to distinguish significant improvement in student performance. Prior studies had characterized significant improvement as being above a 10% increase in PSVT:R [10], [11]. However, this 10% threshold was criticized by a reviewer as arbitrary. We agree with this criticism, and sought a threshold suitable to the possible bimodal component of the data and also reflective of the correlation of PSVT:R scores to graduation rates. Accordingly, we chose as our primary metric for assessment of the effectiveness of the SV training to be the percentage of students who entered the course with a PSVT:R of $\leq$70%, but then raised their PSVT:R to above this threshold. This metric captures gains in SV skills among students that need it the most, and the 70% threshold corresponds to the skill level that is correlated to higher graduation rates.

B. Setting: An Introductory Engineering Course

We conducted this research at the Shiley-Marcos School of Engineering at the University of San Diego (USD). USD is an independent, private, Catholic institution committed to advancing academic excellence, expanding liberal and professional knowledge, creating a diverse and inclusive community, and preparing leaders dedicated to ethical conduct and compassionate service. Unique to USD is the dual BS/BA degree for all engineering students, emphasizing a well-rounded holistic education including an extensive liberal arts core with required classes in ethics, theology, diversity, social justice, and a second language.

All engineering departments at the Shiley-Marco School of Engineering share a common curriculum for three semesters that begins with Engineering 101 - Introduction to Engineering. Given Sorby’s work showing positive impacts on retention, this course was chosen as the site to examine the impact of SV training. The course meets twice a week for two hours and, to maintain small class sizes of 20-30 students, we run roughly eight parallel sections each fall, each with a different instructor. To ensure consistency across the parallel sections, instructors participate in weekly meetings and use the same course materials. In the standard curriculum students do receive some training that is related to, but not explicitly designed for, spatial visualization skills. In one class period students are taught the basics of sketching, including isometric and orthographic projections, and during class hand sketch a 3D printed block. Students also complete two projects over the course of the semester that require computer aided design (CAD). The first project is individual - students use Solidworks to design a small personalized box (4"x2"x3") that they fabricate out of wood using a laser cutter. The second project is team-based - students design and build a hazardous waste disposal vehicle to move simulated nuclear waste barrels to a long term containment facility. A major part of the project is the creation of a detailed CAD model of the vehicle. Teams typically teams divide tasks so that not all of the team members are involved in the CAD portion of the project.

In this pilot study the experimental section (n=23 students) was assigned the spatial visualization app as homework. A second section (n=22 students) was used as a control so that the impact of the existing training students receive could be measured. While there were different instructors for each section, they used the same materials and followed the same lesson plans. After the class activity on sketching (Week 3), students in both sections were asked to complete the PSVT:R assessment. We informed students of the overall research goal and asked them to take the initial assessment seriously, though it was not included in their grade. At the end of the semester students in both sections were again asked to complete the PSVT:R assessment. This time, due to the busy schedule at the end of the semester, students were incentivized complete the assessment with the knowledge that their score could replace a quiz grade if they performed sufficiently well. In both cases the assessment was administered using USD's learning management system (Blackboard). For both assessments students were allowed to see their final score, but not to revisit the questions or see which questions they got wrong.

In the experimental section of the course, students were assigned homework in the app starting in Week 5. For the next 5 weeks students were asked to complete roughly two lessons per week until they had completed all of the spatial visualization modules within the app. For this trial, within each module students were only asked to complete half of the total questions. These assignments overlapped with existing course homework assignments, including problem sets, the box project, and the vehicle project. Other than reminding students to complete assignments and answering occasional one-on-one questions, there was no further discussion of spatial visualization during class time.

C. *Intervention: eGrove Spatial Visualization App*

The Spatial Vis App is a spatial visualization training tool which automatically grades sketches on Android and Apple touchscreen devices. The Spatial Vis App consists of 9 unique lessons and each lesson has approximately 30 assignments. As shown in Figure 2, an assignment window has an image and instructions of what needs to be sketched, a sketching window where the student sketches their solution, a toolbar which provides the students with the tools needed to accurately complete their sketch, and a submit button which initiates the automatic grading algorithm. If the student's submission is correct, they advance to the next assignment, if the student's submission is incorrect, they are given three options: retry, hint, or peek at the solution. Each option offers a different level of help for the student. Retry allows the student to continue working on their submitted sketch, hint shows the student which parts of their sketch are correct, and peek shows the correct and incorrect lines of their submission and the missing lines required to reach the correct solution.

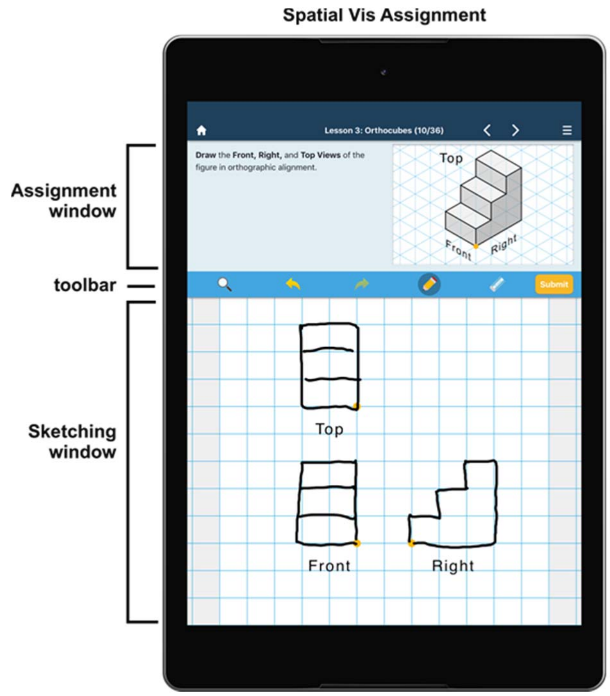

Fig.2. An assignment in the Spatial Vis App.

In a trial of the Spatial Vis app in 2014 [9], it was shown that the more students retried assignments before asking for hints on their own app on, the higher their gains in the PSVT:R post-test. Accordingly, the number of retries was a measure of persistence, which in turn implied a higher level of engagement and effective learning. To encourage students to be more persistent, the app was gamified, and students earned more stars if they solved problems without use of hints [10]. This gamification indeed increased student persistence and PSVT:R post-test gains. It should be noted, however, that due to a software rewrite effort to make the app work on both iOS and Android, the gamification and stars was not in place during the USD trial described in this paper.

Another difference between the 2014 Spatial Vis App and the version used in this study was the sketching assignments. The 2014 study assignments were taken from a workbook for SV training [19]. Since then new assignments were created specifically designed to take advantage of the touchscreen interface [10]. Color was used as scaffolding in early assignments, and assignment difficulty was gradually increased.

III. Results

To examine whether students spatial visualization skills improved, we conducted a pre/post assessment with the PSVT:R instrument. When evaluating the students in both the experimental and control groups there were statistically significant increases between the pre- and post-test scores. All students in the experimental section had a mean gain of 14 points (σ=18.7, paired t-test t=3.673, P=0.001), while the control section had a mean gain of 8 points (σ=16.2, paired t-test t=2.248,p=0.036). Comparing these gains between the two groups, however, yielded a statistically insignificant result (pooled t-test t=1.210, p=0.233, mean difference 95% percent confidence interval: -4.3 to 17.1). Our data revealed there is a large standard deviation on student gains, meaning that in order to draw statistically significant conclusions we will need to increase the number of students in our study. For example, suppose we want to detect a difference in student gains of 10 points between the experimental and control group. If we assume $\sigma=18$, as we saw in the pilot study, to achieve a reasonable statistical power (p=0.8) at $\alpha=0.05$, our study will require a trial with $n\approx 50$ in both the experimental and control groups. If it turns out that the difference between the gains is only 5 points, however, using the same assumptions we would need a study with $n\approx 200$ in both groups. In future studies we will need to substantially increase the number of participants if we wish to directly evaluate student gains.

However, as noted in the Methodology section, the effectiveness of SV training can also be assessed by the number of students who have a pre-test score of $\leq$70%, but were able to surpass the 70% threshold on the PSVT:R post-test. This group is of specific interest because the literature suggests these students are at higher risk of leaving engineering due to low SV skills [4]. The literature has also shown that if these low-performing students can achieve scores higher than 70% through SV training, then their graduation rate can be brought up to close to those students who started with a higher PSVT:R score.

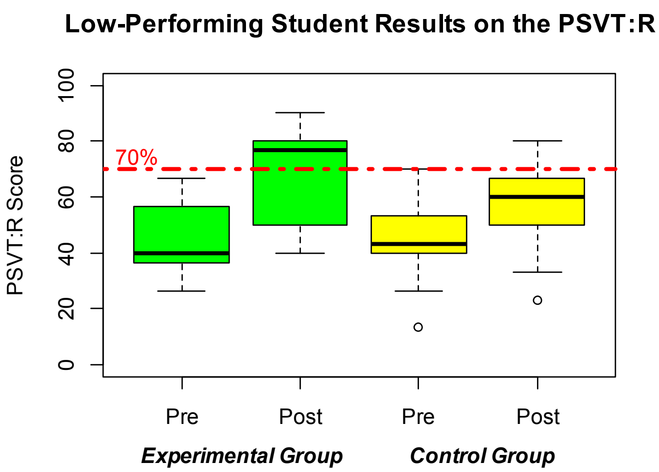

Fig. 3. A box and whisker plot showing low-performing student performance (in points, out of 100) on the PSVT:R instrument. 8 of 13 (62%) low-performing students raised their test score above the 70% threshold.

Students that started with low pre-test scores showed remarkable progress in the group that used the Spatial Vis app; 8 of 13 (62%) raised their test scores above 70%. As a group, these students saw an average improvement of 23 points on their scores ($\sigma=16.1$, paired t-test t=5.050 , p<0.001). In the control group, only 2 of 14 (14%) low-performing students succeeded in raising their score above 70%. They saw their scores increase on average by just 14 points ($\sigma=16.9$, paired t-test t=2.631 , p=0.020). The difference in these gains did not meet the threshold for statistical significance, again due to the small sample size and large standard deviation (pooled t-test t = 1.67, p-value = 0.11). We do argue, however, that the number of students that shifted categories is meaningful. As discussed in the methods section, the PSVT:R is a robust instrument that has been shown to accurately measure student performance before and after interventions (Cronbach's α = .81). The percentage of students using the app in the low-performing group that crossed the 70% threshold far exceeded the control section (62% vs. 14%). Furthermore, their post-test score average was 80.8 (σ=5.0), an indication that the results were not a "barely passed" phenomenon. This evidence supports the conclusion that the Spatial Vis app has a sizable impact on helping students move out of the low-performing group.

IV. Conclusion

SV training, and specifically isometric and orthographic sketching, has be shown to increase graduation rates in engineering for students entering with low SV skills. Few engineering curricula, however, include SV training, and adding new content to an already full program can be difficult. Accordingly, the potential for SV training that could be done by students outside of scheduled class time is attractive. The Spatial Vis App was designed to meet this need as it allows for freehand sketches to be graded automatically and for hints to be provided when needed.

In this study we examined the effectiveness of the app in a controlled setting. The SV training was assigned primarily as homework, so lecture time was not impacted and students who needed more time to complete the assignments could do so at their convenience. Most noteworthy was that a control section was held side by side with the experimental section – something that had not been tried for eGrove Educations's app.

Students using the app appeared to show substantial progress, however due to the small size of the pilot study the gains between the experimental and control groups are not statistically significant. That said many low-performing students who used the app (8/13) were able to raise their post-test score above the 70% threshold. The literature indicates that these gains can significantly increase graduation rates in Engineering.

Future work will focus on multiple areas. First, this study will be replicated at USD with a larger sample size to include all of the first-year engineering students ($n\approx 200$). This study will be used to confirm the results seen in the pilot study and to provide further evidence that the number of students who surpass the 70% threshold due to the App is not a statistical aberration. Second, we plan to measure the impact of the Spatial Vis app with other student populations – including at large state schools and high schools. With positive results, we hope to scale up the use of the Spatial Vis app so that all students will have a resource to help them develop their spatial abilities.

IRB Compliance

This study was conducted under University of San Diego IRB-2017-257. All appropriate considerations were taken for research with human subjects.

Author Contributions

ND, GH, and LC performed the analysis and wrote the manuscript. ND, LC, LV, and JT developed the Spatial Vis app. GH taught the course.

Conflict of Interest Disclosure

ND and LV have equity interest in eGrove Education, Inc., a company that may potentially benefit from the research results. The terms of this arrangement have been reviewed and approved by the University of California, San Diego in accordance with its conflict of interest policies. In addition, a Small Business Innovation Research (SBIR) grant was awarded to eGrove Education, Inc, by the NSF (Award # 1648534), that also supported the research effort of this publication.

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