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Using Digital Sketching and Augmented Reality Mobile Apps to Improve Spatial Visualization in a Freshmen Engineering Course

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Spatial reasoning skills contribute to performance in many Science, Technology, Engineering and Mathematics (STEM) fields. There is considerable variation in the spatial reasoning skills of prospective engineering students, putting some at risk for compromised performance in their classes. This study takes place in a first-year engineering Spatial Visualization course. The course endeavors to integrate the use of current technology and online accessibility to bring about student growth in spatial reasoning. The study is designed to determine the effect of adding two different spatial reasoning training apps to this environment. Over 110 students (three sections) participated in our study. In one of the three sections, students completed interactive spatial visualization weekly assignment using a spatial visualization mobile sketching app. In another section they used an Augmented Reality (AR) app. The third section was a control group that completed traditional hand sketching assignments on paper. All course sections were required to use the apps or do the paper hand sketching assignments for approximately the same time in class and outside of class. Our first hypothesis that overall benefits (PSVT-R gains) will be comparable across the 3 treatments was corroborated. Results suggest that there was significant growth in measured spatial skills but not a significant difference between group treatments. We also hypothesized that the treatments will have different effects on male/female and ethnic categories of the study participants. This hypothesis was partially corroborated. This paper reports on the findings when using digital sketching and augmented reality mobile apps to improve spatial visualization skills of first-year engineering students identified with low spatial skills.

Keywords: spatial reasoning, apps, augmented reality, engineering education

I Background

Spatial visualization is the ability to mentally represent and manipulate two-dimensional (2D) and three-dimensional (3D) figures. Spatial skills are often used in STEM careers, such as those in engineering and medicine, and have been positively correlated with increased grade point averages and retention in STEM-related fields, including math, engineering, computer programming, and science [1, 2]. Spatial visualization skills are learnable [1, 3, 4], but most students do not receive formal instruction in K-12 or at the university level. In addition, a particular lack of exposure to spatial visualization skills may explain why women and other underrepresented minority (URM) students are less likely to choose and retain engineering and STEM as a major and as a career. A 2010 report "*Why so Few? Women in Science, Technology, Engineering, and Mathematics*" identified spatial visualization as an important skill in STEM courses, and cited statistics that women and other URM groups have, on average, lower spatial visualization skills prior to any formal training [5]. The clear need for improved and more broadly available spatial visualization education and training has led to the development of college-level spatial visualization courses [4, 6].

Evidence suggests that such courses do have a positive effect on both spatial visualization skills and retention in STEM majors, especially for women and other URM groups as well as those starting out with poor spatial visualization skills [2, 3, 7]. Typical spatial visualization training is a combination of multiple choice problems and freehand paper-and-pencil sketching assignments, but these can be less than ideal for two reasons: 1) multiple choice questions can be answered correctly using a process of elimination and the correct answer is visually available (and for this reason do not necessarily translate into real-world understanding or application), and 2) while sketching appears to convey greater benefit, paper-and-pencil sketching assignments require more instructor time for grading and often do not allow for immediate feedback and back-and-forth teaching.

As described above, sketching is an important part of the engineering design process and an integral component in learning spatial reasoning skills. Instructors have struggled in the past to find a way to provide students with significant sketching practice since it is too cumbersome to manually grade sketching assignments in such a large class. Recently, in spatial visualization and design training, educators have taking advantage of current technology to create apps and offer students more flexibility in their development and enhancement of spatial skills. For example, the Spatial Vis App developed by Delson and Van Den Einde (2015) runs on touchscreen Apple and Android devices and allows students to mentally rotate 2D and 3D objects and sketch a variety of shapes [4]. This app provides students with immediate feedback, including personalized hints, and visual presentation of the correct answer in contrast with the student's submitted sketch. It also provides animations and the use of color to take advantage of the digital interface (see https://www.spatialvis.education/). Figure 1 shows a screenshot of the Spatial Vis app.

Figure 1: User Interface of Spatial Vis App

Preliminary research conducted by the creators of the app suggests that there are benefits to using the Spatial Vis app for college students, particularly for those entering with poor spatial visualization skills [8]. The app has been shown to increase student persistence resulting in large learning gains as measured by the Purdue assessment of spatial visualization (PSVT: R), especially for students starting with poor spatial visualization skills.

Another app, called Spartan SR, is an augmented reality app designed to help users develop their mental rotation abilities. It supports a holistic understanding of 3-dimensional objects, and research has shown that, in combination with traditional curriculum, it increases students' abilities also measured by the PSVT: R. Spartan can be use on handheld augmented reality on smartphone and mobile tablet devices (see Figure 2). The app allows users to move physically around a fiducial marker in order to view virtual objects from multiple angles. Users can also rotate the objects along major axes. Of particular interest, the data suggest that the app overcomes the advantage found by males over females in a traditional class alone focused on spatial reasoning [9]. Figure 2 shows a screenshot of the user interface for the Spartan AR app.

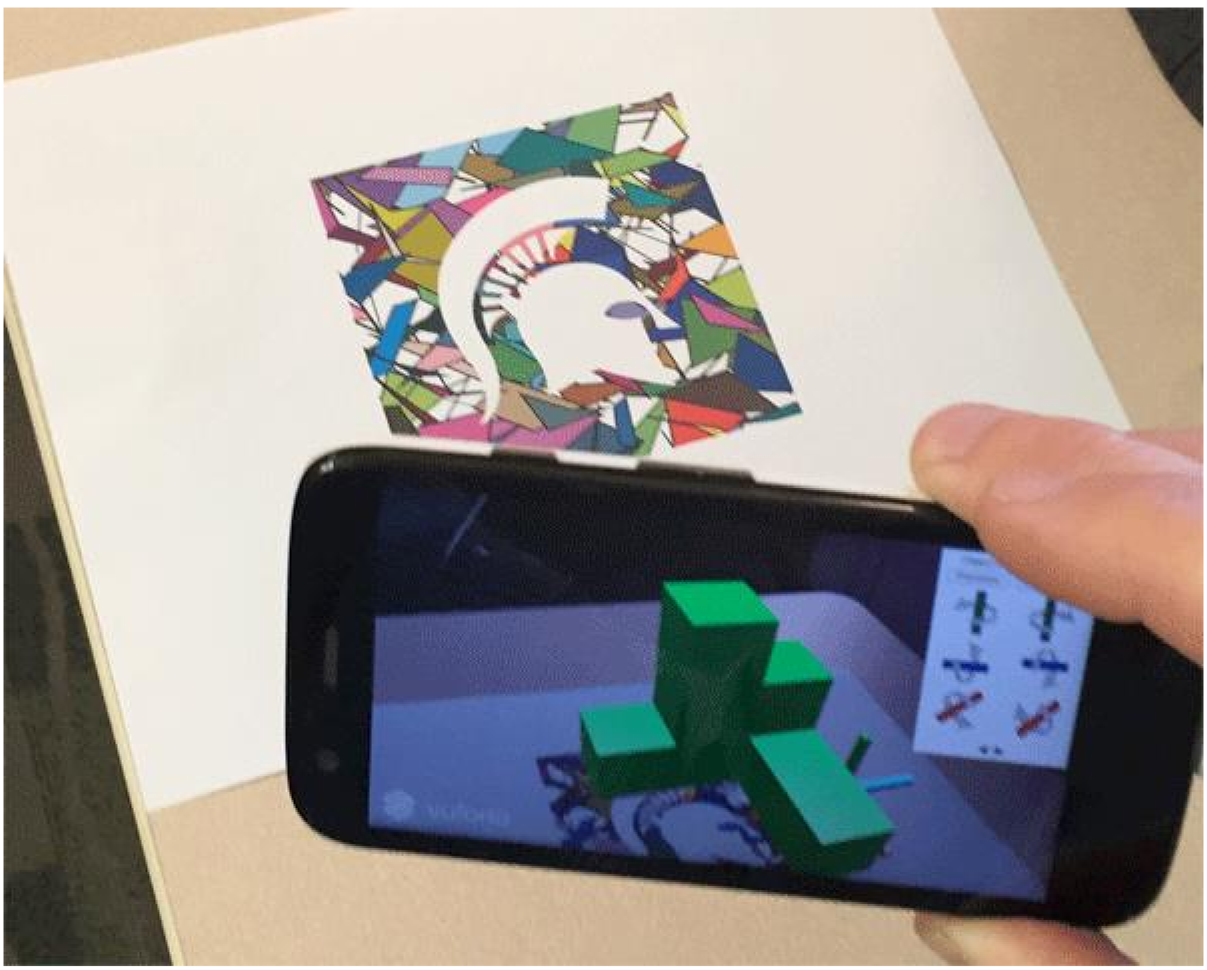

Figure 2: User Interface of Spartan AR app

The above described apps can be used in the classroom or assigned as homework and they allow students to rotate and visualize 2D and 3D objects independently on a touchscreen and get instantaneous feedback without the need for instructor grading. Improved spatial visualization skills are linked to improved engineering graphics and design capabilities. Within this study we are interested in assessing the impact that the Spatial Vis and Spartan AR app have on students to ultimately improve engineering education.

II Study Design

This study takes place in a first-year Introduction to Spatial Visualization course at a large public university in the Southeastern U.S to integrate recent practices in engineering design education with cognitive psychology research on the nature of spatial learning. We employed three main pedagogical strategies in the course - 1) in class instruction on sketching; 2) spatial visualization training; and 3) manipulation of physical objects (CAD/3D print creations). This course endeavors to use current technology, online accessibility, and implementation of the three pedagogical strategies to bring about student growth in spatial reasoning. This study is designed to determine the effect of supporting student practice with spatial reasoning activities using the two different spatial reasoning training apps to this environment. The instruction and in-class activities remained the same across the three sections.

The two trial course sections were required to use the apps for approximately the same time, including time in class and outside of class. Students in the control section were required to do hand sketching activities in class and outside of class, also with roughly the same completion time as for the sections with the apps. Students grades were not affected by using the three different approaches as grading was based on completion only.

A quantitative method was selected to assess the effectiveness of the assignments in the digital sketching and augmented reality mobile apps and address the two study hypotheses: H1) Whether overall benefits (spatial test gains on the SBST and PSVT: R assessments) will be comparable across the 3 treatments, and H2) whether the treatments will have different effects on male/female category of the study participants.

Participants

One-hundred-and-nineteen students (52 female, 67 male) from three sections of the first-year engineering course participated in this study. The course was designed for students with low spatial skills as measured by PSVT: R. Students enrolled in the Spatial Visualization course scored 18 or below on the Purdue Rotation Visualization Test: Revised (PSVT: R) administered to them during summer before their freshman year.

Data Collection

Students' spatial skills were assessed with the PSVT: R [10] and the Santa Barbara Solids Test (SBST) [11]. The tests were evaluated in previous studies and had been used in prior research on the role of spatial skills for engineering spatial visualization training [11, 12, 13]. The tests were provided online using a Qualtrics survey to students at the beginning and end of the course. All participants took the two tests during class and had 20 minutes to complete the PSVT: R and 12 minutes for the SBST measure. The PSVT-R consists of 30 questions that require participants to solve spatial problems related to rotations and isometric views [10]. Figure 3 shows an example of a PSVT: R question.

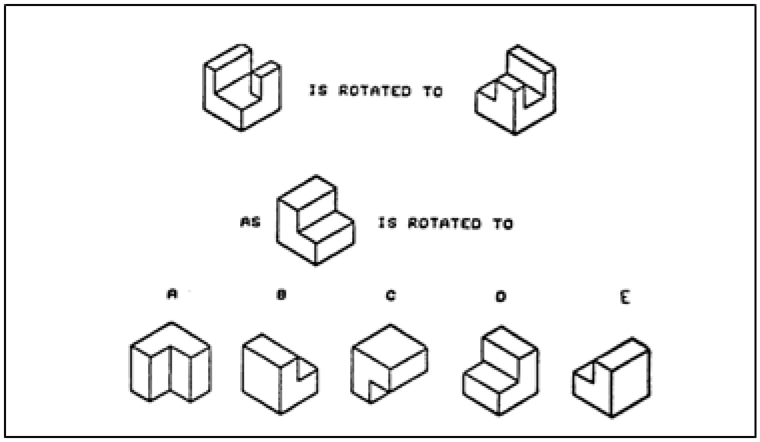

Figure 3: A sample problem from the Purdue Spatial Visualizations Test: Rotations

The SBST is a 30-item multiple-choice test in which participants are asked to solve spatial problems related to cross-sectional views (Figure 4). Half of the figures have cutting planes that are orthogonal (horizontal or vertical) to the figure's main vertical axis; the other half have cutting planes that are oblique to the main vertical axis [11].

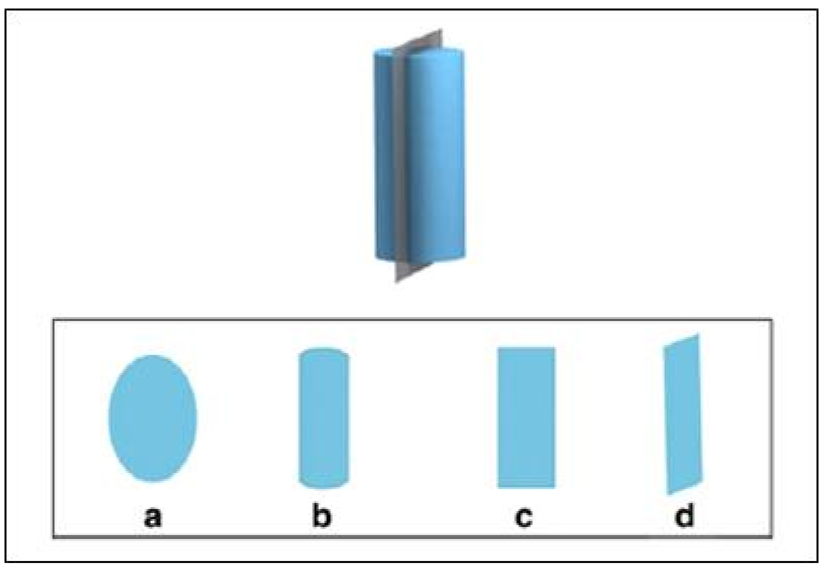

Figure 4: An example from Santa Barbara Solids Test

The study received IRB approval. There were no risks to the students related to participating in this study, and study participants did not have any costs or liabilities different than the control group participants. Students in the two treatment groups using the apps were not required to purchase a device to do the assignments or participate in this study. There were no incentives given, such as extra credit.

All three groups received the same instruction in class for through the whole semester. Students in all three groups moved through the course in three modules: 1) sketching, 2) CAD, and 3) 3D object design and creation. During the sketching module, students were introduced to orthographic projection theory, sectional views, and learned how to interpret engineering drawings. During the second module, students learned how to navigate the new user interface and features of INVENTOR (the CAD software used in the course) and practiced designing simple solids for four weeks. In the final module, all students were introduced in class to additive manufacturing, a step-by-step guide on developing slt. files in order to 3D print each basic solid they designed. At the end of the third module, students prepared their 3D printed objects for an outreach event at a local Senior Citizen's Home.

The difference between the three sections was in the methodology that students practiced the above described instruction, and particularly in the rotations of simple solids. During weeks 6 to 16 of the semester, the participants in the two trial sections used the Spartan AR and Spatial Vis apps respectively as part of their class interactive spatial visualization training. Training time with the apps targeted 40-minutes, starting with 10 minutes in class, followed by 30 minutes required homework time outside of class. Students were graded on completion and time spent on the tasks. All participants who completed the weekly homework assignments received 25 points. The use of the apps was considered as a teaching choice rather than an intervention. Participants (n=38) in the group using the Spartan SR app completed nine weekly homework assignments. Topics ranged from 3D rotation prediction games to folding games. Users were given an AR object and asked to select choices from a drop-down list to answer specific questions. After answering the multiple-choice questions, students were provided with animations to better describe the solutions. Figure 5 shows an example of a 3D rotations assignment in the Spartan 3D app.

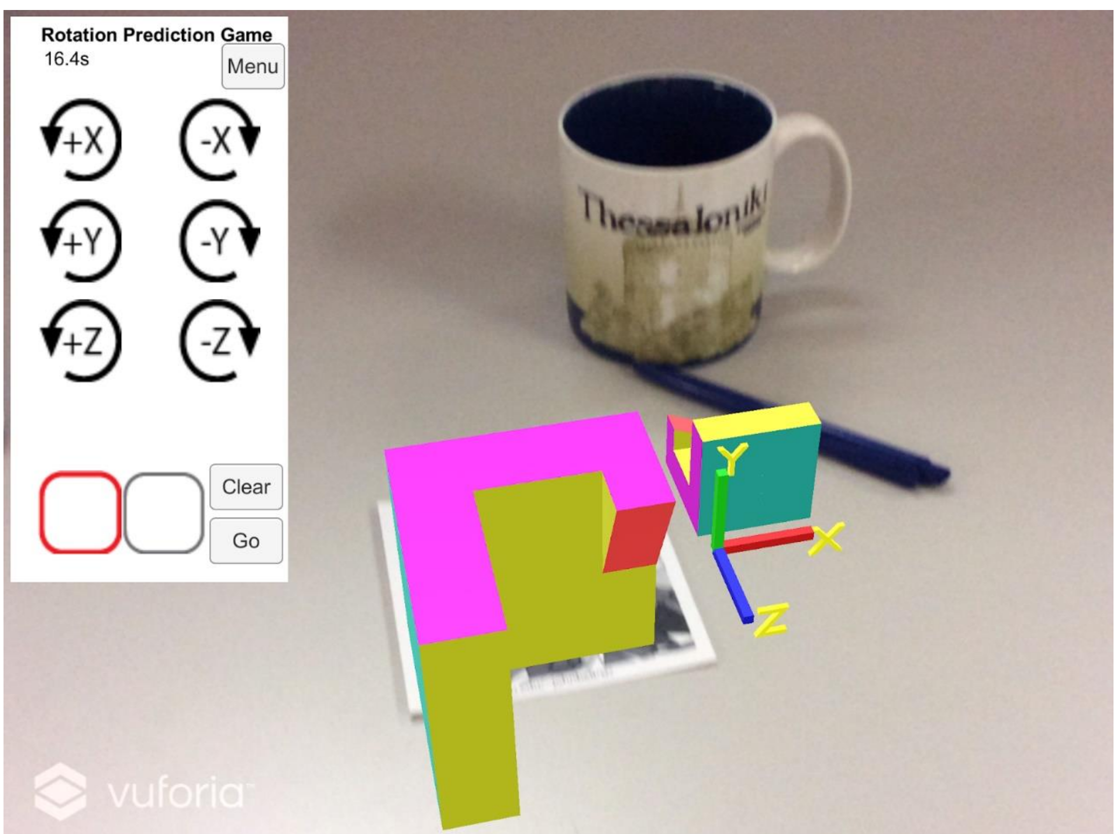

Figure 5: Sample 3D Rotation prediction game in Spartan AR app

The participants in the Spatial Vis app also completed nine homework assignments consisting of hand sketching objects on a touchscreen that rotated in 2D, orthographic projections and isometrics, unfolding shapes into flat patterns, 3D rotations about one and two axes, and an assembly module that resembled a soma cube. Figure 6 shows a sample assignment from the Spatial Vis App requiring students to draw an isometric from three orthographic projections. In this app, students are able to retry an assignment as many times as needed to solve the problem. To encourage persistence, students receive three stars for each assignment they solve correctly without any assistance regardless of how many times they attempt the sketch. If a hint is used, then they are awarded two stars for the problem and if a peek is used then students earn only one star when they successfully complete the sketch.

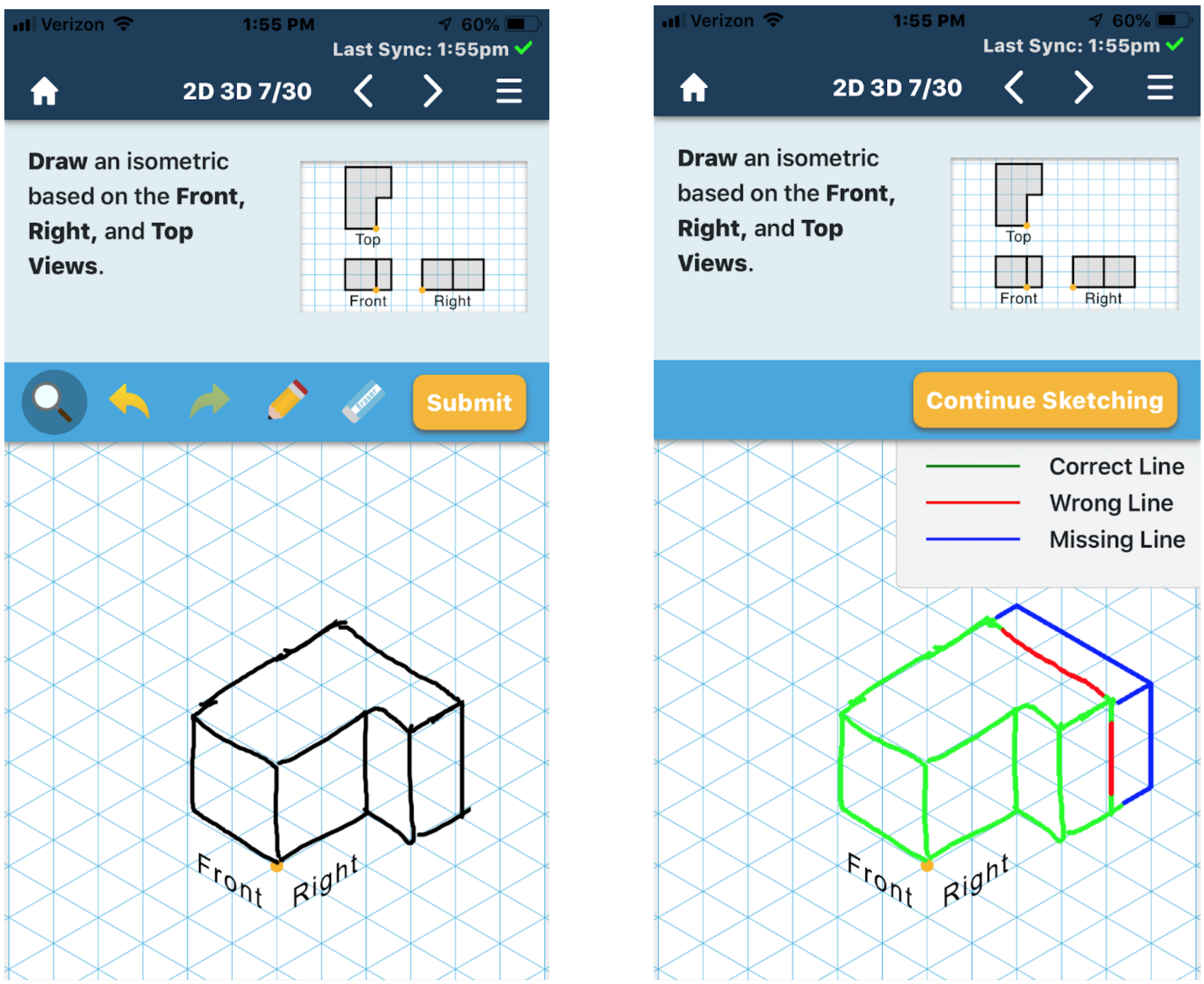

Figure 6: An assignment from the 2D to 3D module where students create an isometric drawing from orthographic projections. Grading algorithm on right shows feedback for an incorrect sketch.

A weekly free-hand sketching assignment distributed through nine weeks was given to the control group (n=42). These assignments consisted of a similar number of likeminded sketches as in the Spatial Vis app and Spartan app. For example, one of the drawing assignments asked students to manually draw sectional views of six mechanical objects using a cutting plane as shown in the Flange example in Figure 7. Students were asked to sketch the sectional view of the part below by using the identified cutting plane line to do the imaginary cut.

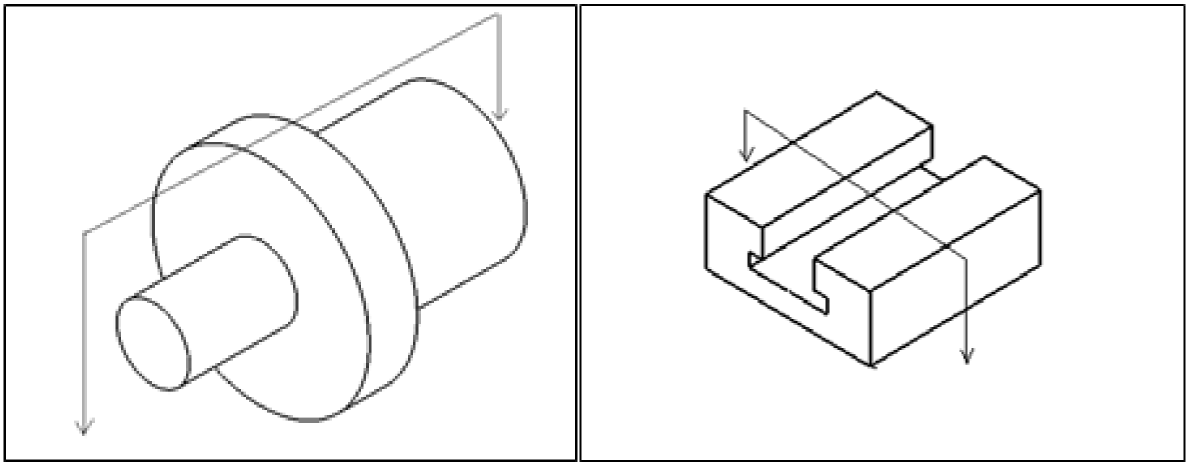

Figure 7: An example of a 3D drawing of a Shaft and a Tee Slide

Analysis

To test if there were overall gains, two ANCOVAs were run with the post scores (PSVT: R and SBST) as the dependent variables, the treatment group as the fixed factor, and the pre scores (PSVT: R and SBST) as the covariates. In short, we wanted to know what effect the different treatments had on the posttest scores while controlling for the variation in the pretest scores. We also calculated pass rates and change in pass rates.

III Results

All pre- and post-test scores met statistical assumptions of normal distribution, linearity, and homoscedasticity. Therefore, the ANCOVAs were sound to be conducted.

Pre-to-post PSVT: R

Students in the three groups showed significant increase in performance on the PSVT: R from pre-test (M=.564, SD=.157) to post-test (M =.662, SD = .152), $F(1, 119)=73,144$, $p<.000$, partial η 2 = .648. The significant increase means the null hypothesis is accepted for H1 regarding the PSVT: R. Across genders, there were no significant differences in PSVT: R performance $F(1, 119)=2.69$, $p=.136$, partial η 2 = .030. Therefore, the null hypothesis is accepted for H2 in terms of the PSVT: R. The class average growth from pre to post PSVT: R was 8%.

Pre-to-post SBST

Students showed a significant increase in performance on the SBST pre-test (M=.567, SD=.219) to post-test (M=.706, SD=.183). Significant main effect on plane $F(1, 119)=60.033$, $p=.000$, partial η 2= 1.35. Across genders, there was no significant differences in SBST performance. Therefore, the null hypothesis for H1 is rejected and accepted for H2. The class average growth from pre to post SBST was 15%.

Across treatments, there was no significant difference in post-pass scores. For pass scores we looked at number of correct answers on PSVT: R equal or more than 18. Tables 2 and 3 show the number of students in the three groups who passed or failed the threshold.

Table 1. Pre PSVT: R number of participants who passed/failed the threshold

	<70%	*>=70%*	*<60%*	*>=60%*
All	93	26	71	48
Group 1	33	5	23	15
Group 2	27	13	18	22
Group 3	34	8	31	11

Table 2. Post PSVT: R number of participants who passed/failed

	<70%	*>=70%*	*<60%*	*>=60%*
All	72	47	40	79
Group 1	23	15	10	28
Group 2	18	22	11	29
Group 3	32	10	19	23

In summary, the analysis revealed that there was overall significant growth in both PSVT: R and SBST tests for all students despite the different teaching approaches. However, there was no significant difference in PSVT: R and SBST by treatment, meaning that the first hypothesis was corroborated. The treatments did not have different effects on male/female category of the study participants as there was no significant difference in PSVT: R and SBST by gender in treatment 1 (Spartan app), treatment 2 (Spatial Vis) and treatment 3 (free-hand sketching). However, male participants using the Spartan app grew significantly more on PSVT: R than the female participants in treatment 1 - (M=.705, SD=.106), $F(1, 38) = 6.29$, $p<.017$. Thus, hypothesis 2 is partially accepted. Finally, there was a significant difference in *pre*-pass scores as follow - participants in treatment 2 (Spatial Vis app) had the highest initial PSVT:R scores, followed by participants in treatment 1 (Spartan app), followed by participants in treatment 3 (free-hand sketching) - (M=.395, SD=.491), $F(1,119) = 3.336$, $p<.039$. There was no significant difference in post-pass scores, regardless of treatment.

IV Discussion & Conclusion

It has long been confirmed that spatial reasoning skills can be learned. Since this study targeted a first-year engineering course dedicated to teaching spatial reasoning skills it was expected that students would see learning gains regardless of the tool used to teach the material. This study integrated the use of the Spartan AR app and the Spatial Vis sketching app in comparison to a control group that used hand sketching exercises with paper and pencil. As expected, all three sections showed gains between their pre- and post- assessments. Time spent on the tasks were similar across all three sections. In general, there were no major differences between the performance of males and females for the different treatments.

The instructor of the course liked the interactive nature of both apps and that students could work independently (critical for a large class size). For both apps, it was easy to assign the modules as homework, which aligned well with the hybrid learning approach the instructor was applying in the three sections of the course. It was helpful to students and the instructor that both apps provided immediate feedback. In general, students in the three groups were engaged during class while working on the apps or on the free-hand exercises. Not surprisingly, the sections with the apps showed more excitement when working in class. The homework assignments were graded based on completion rather than on right answers since the instructor was concerned that providing a different incentive might result in students in the treatment groups being more motivated to spend more time on the assignments, therefore, to perform better. Alternative incentives, such as extra credit based on better scores in these apps, needs to be considered when studying the use of the apps to understand what contributes to learning gains, including the possibility of students choosing to spend more or less time in different interventions. Further, it will be of value to study how different feedback (immediate with the apps and late with the free-hand assignments) affects performance. This will be one of the goals of a future study described below.

A self-assessment survey was conducted to ascertain student's perception of the effects of the two spatial visualization treatments on their spatial reasoning skills. In general, almost all students felt that the apps helped their spatial reasoning skills a great deal or a bit regardless of the app used. When asked "*When did you mostly work on the app*?", many students for both apps responded during their free time, at the library, or in their dorm. Students' favorite aspects of the Spartan SR app were its ability to be used wherever, and they found it fun to use their phone like playing a game. Students liked the ability to change their views and see the axes rotate and to interact with virtual objects through their phones the same way that they would take a picture of physical objects. For the Spatial Vis app, students really enjoyed the ability to sketch assignments digitally, and they liked that the app gave hints so they could figure out difficult problems. Conversely, students did not like how the Spartan SR app crashed a lot due to bugs and glitches. For the Spatial Vis app, students were frustrated about having to draw lines precisely and they mentioned that having a larger screen size would be preferred.

Overall, the study was successful in demonstrating that the use of technology for practice of spatial reasoning activities is as effective as standard approaches. We suspect that motivation plays a huge role in PSVT: R gains and will look into these aspects in a future study. Furthermore, we will also further analyze the data from the self-evaluation surveys to determine if the three treatments result in different effects on attitude and engagement (confidence, enjoyment, and selfefficacy). Finally, we hope to rerun the study with a different cohort to obtain a larger sample for general publication.

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