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Improving Spatial Visualization Skills of High School Students Through Sketch Training on a Touchscreen (Evaluation)

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Abstract

This paper evaluates an approach for training and improving high school students' Spatial Visualization skills. Using touchscreen devices from home, 45 high school juniors and seniors enrolled in an educational application consisting of nine lessons on drawing orthographic and isometric figures. As part of their remote instruction during the COVID 19 pandemic, engineering students downloaded the application onto their cell phone or tablet and completed a series of auto graded exercises that were assigned in their high school course. The application included gamification features such as stars for rewards and hints to encourage student persistence. The Purdue Spatial Visualization Test: Rotations (PSVT:R) was administered before the treatment and the mean score for the participant group was 74.0% Regardless of their pretest score, participants were required to complete all nine lessons in the application. After course completion, a post-test of the PSVT:R was administered and the mean score for the participant group improved by 6.3%. Results showed that students who were classified in the at risk low performing group and had a pre-test of 70% or lower improved on their post-test score by 15.6%. Sex differences were examined, with female students improving their post-test score on average by 10.7%. Of the nine female participants, five started in the low group and three out of those five ended up moving out of this at-risk group. Additionally, a 15 question evaluation survey was administered to gather student opinions about their user experience.

1. Introduction

Spatial visualization skills have been linked to student success in science, technology, engineering and mathematics (STEM) subjects in school [1, 2, 3, 4, 5] and to the likelihood of participation in a STEM undergraduate degree and career [6, 7]. Some groups of students from underrepresented populations in STEM seem to struggle with spatial visualization skills [1, 2, 3, 8]. Spatial skills are not innate, however, and research shows that students weaker in these skills can improve with training [1, 2, 3, 9, 10]. With the demand for more STEM professionals K-12 educators are hard pressed for curriculums and activities that hone these skills. For this reason, the National Academies of Science have called for scientists and educators to develop systematic programs that improve spatial thinking skills [6].

1.1 Background

The 2020 global pandemic brought about an urgent need for meaningful online engineering curriculum and activities. The creative use of teleconferencing applications with breakout rooms and learning management systems like Google classroom allowed for many successful interactions between teachers and students. However, high school engineering programs struggled to provide students with hands-on experiences because all activities had to be limited to materials and supplies found in the students' home.

In fall 2020, instructors and administrators for a dual credit engineering course offered in 35 high schools across the USA Southwest were looking for online solutions. Early in the school year students in the course typically completed hands-on activities in the classroom that improved spatial visualization skills such as paper and pencil drafting exercises and soma cubes. *Spatial Visualization* is the ability or skill drawn upon to mentally transform or manipulate spatial properties of an object [5]. Assessment and grading for these sorts of activities was complicated in normal times and with the shutdown was even more difficult. A decision was made in two classrooms to use a spatial visualization application (App) and online curriculum that students could access on their phone or tablet.

Spatial Vis is a personalized learning environment developed by eGrove Education, Inc. to teach spatial visualization skills through sketching. It runs on touchscreen Apple and Android devices as well as advanced chromebooks and allows students to mentally rotate 2D and 3D objects and sketch the Top, Side, and 3D views for a variety of shapes. [11]. The platform provides automatic grading and instantaneous personalized feedback to students as if an expert teacher is looking over the student's shoulder thereby making the technology suitable for in person or remote instruction. The platform is gamified and engaging to encourage student persistence (see https://www.egrove.education/). Figure 1 shows a screenshot of the Spatial Vis App. The Spatial Vis App has shown positive outcomes for undergraduate engineering students and is in use in multiple engineering courses across the nation [12, 13].

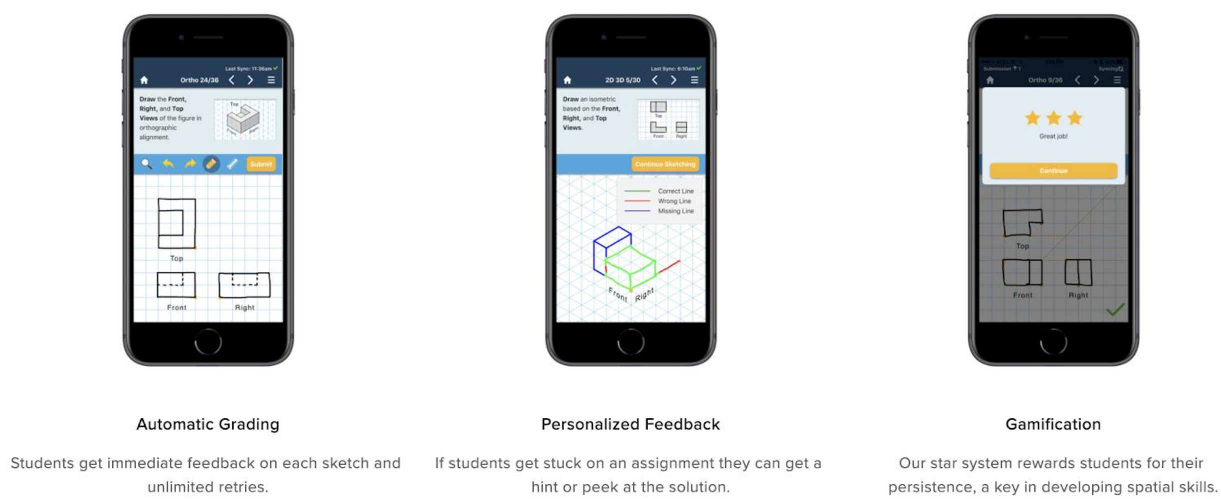


Figure 1. Spatial Vis sketching App

1.2 Framework and Definitions

The terms *spatial reasoning* and *spatial visualization* are often incorrectly used interchangeably. Spatial reasoning involves three properties: 1) an awareness of space, such as distance and dimensions; 2) the *representation* of spatial information, in the mind or in maps or blueprints; and 3) the reasoning involved in interpreting this information for problem solving [6]. Thus, spatial reasoning comprises a range of spatial skills and includes skills like mental rotation, spatial orientation and spatial visualization.

Table 1. Properties of Spatial Reasoning

Properties of Spatial Reasoning	Examples of Spatial Reasoning skills
● Awareness of space ● Representation of spatial info ● The reasoning involved in interpreting this info	● Mental rotation ● Spatial orientation ● Spatial visualization

Mental rotation is a specific type of object-based orientation that tasks the 2D or 3D objects to remain intact during its rotation [3]. Skills with mental rotation have been linked to early mathematical development due to shared processes of constructing and manipulating mental models [14]. Spatial orientation is the ability to orient *oneself* in space. For example, to find your way home based on landmark ques, or the ability to find your way around a large convention center- locating exits or the food court. Spatial visualization, the spatial reasoning skill that is the focus of this paper, is the comprehension of the arrangement of elements within a visual stimulus pattern and the ability to mentally manipulate those elements [15].

Working on spatial visualization skills via an educational application fosters a student's *Self-Regulated Learning (SRL*) as well as intrinsic and extrinsic rewards. Descriptions of a student with strong SRL skills often differ on the basis of researchers' theoretical orientations, "…a common conceptualization of these students has emerged as metacognitively, motivationally, and behaviorally active participants in their own learning" [16]. Intrinsic motivation refers to behavior that is driven by internal rewards. In other words, "…the motivation to engage in a behavior arises from within the individual because it is naturally satisfying" [17]. SRL relies on intrinsic motivation in that the student finds the motivation to learn based on their personal desire to succeed. Educators understand the power of intrinsic motivation in shaping desired behavior, but it can be elusive. Intrinsic rewards are not always motivating for all students. We cannot overlook the usefulness of an A+, a sticker or treat in motivating learners of all ages. Extrinsic motivation in the form of rewards can also play an important, though less desired, role in creating meaningful learning experiences for all kinds of learners.

2. Evaluation Methods

This evaluation takes place in two high school engineering classrooms in the USA Southwest. The participants were enrolled in a dual credit introduction to engineering course that was partially online due to the 2020 pandemic. Students were given the Purdue Spatial Visualization Test: Rotations (PSVT:R) before the treatment lessons and participants were required to complete all nine touch screen lessons in the application as part of their course [18]. The provided powerpoint lectures were delivered live online by the high school teacher and students were assigned the associated touchscreen lessons as homework. After completion, a post-test of the PSVT:R was administered. Both classrooms followed a similar curriculum as part of their dual credit course and began the treatment spatial visualization lessons in October and completed the post-test before the December winter break.

2.1 Participants

Participants were 36 male (80%) and 9 female (20%) high school juniors and seniors in a dual credit engineering course. With a focus on using an online solution for high school engineering content, two public high school classrooms taught by two different teachers, participated in this evaluation. High school A has a student population that is 32% Hispanic, 31% White, 25% Black, 4% Native American and 8% other races. 28% of the students in High School A are on free and reduced lunch. High school classroom A consisted of one junior and 21 seniors who had been enrolled in two or more engineering courses throughout their high school career.

High school B has a student population that is 48% white, 22% Hispanic, 16% Asian, 8% Black, 6% other races and 19% of the student population in High School B are on free and reduced lunch. High school classroom B consisted of all senior students enrolled in their first engineering course, however, they had a week-long drafting lesson and some introduction to CAD earlier in the school year. Of the 45 students tested, all but three students completed both the pre and post-assessment, these three students were excluded from the analysis because of the missing data.

2.2 Instruments

Students' performance was assessed using the PSVT: R [18], to measure student proficiency on spatial visualization skills. The PSVT: R is a 30 multiple choice question assessment on identifying correct object orientation based on a particular rotation. Participants had 20 minutes to complete the PSVT:R using an online learning management software (Schoology or Canvas) in a hybrid school environment. Due to the pandemic, schools on a hybrid schedule met in person 2 days a week and online during the remainder of the week. Spatial Vis lessons were then assigned as part of the students' regular schoolwork. After treatment, the PSVT:R was administered again as a post-test. Additionally, students participated in a 14 question survey about their perceptions of the spatial visualization App as well as their personal opinion on the development of their spatial visualization skills.

2.3 Analysis

The average scores on the pre- and post- PSVT:R test were analyzed for classroom A, classroom B, the entire group, as well as female participants. Of specific interest are students who scored low on their pre-test. In this analysis the student's whose pre-test was $\leq$ 70% are categorized as "at risk" for low graduation rates in future STEM undergraduate programs due to low Spatial Visualization skills [3].

Within the "at risk" group, the average gains in PSVT:R scores does not tell the complete story, and prior studies have shown that learning gains between the pre- and post- tests are correlated to students' persistence [11], which is measured by the number of times a student retries an assignment without taking a hint or peek. Because this data was not available for this study, we evaluated the average stars that students earned within the App which measures, to a certain extent, how often a student is hinting or peeking. Students who are persistent and who try an assignment as many times as they want until they get the solution without taking hints or peeks will have average stars close to 3. Considering an average of 30 assignments per lesson, students with average stars below the first threshold of 2.78 which is flagged yellow means the student hinted on at least 25% of the assignments. If their average stars dips below the second threshold of 2.55 that is flagged red, the student peeked on 25% or hinted on 50% of the assignments (not counting assessment test questions).

Another metric to assess the effectiveness of the spatial visualization training was the percentage of students who scored 70% or lower on the PSVT:R but then raised their PSVT:R to above this threshold. This metric captures gains in spatial visualization skills among students that need it the most, and the 70% threshold corresponds to the skill level that is correlated to higher graduation rates in STEM. This metric can be seen as an indicator of the percentage of students who moved from the "at risk" category for low graduation rates due to low SV skills, to outside of this category. Effectiveness of SV training can be characterized by the percentage of "at risk" students who have pronounced gains in PSVT:R scores [12]

The survey results were also analyzed. Questions based on a 5 point Likert scale were quantified. For text answers, the responses were classified based on the emergence of themes. These results are summarized in the next section.

2.4 Results

The results of the pre- and post- PSVT:R are summarized in Table 2. The average test scores for each classroom (A and B) are provided as well as average for all participants in the study. The last column shows the average percent increase between pre- and post- test. From the first three rows of Table 2, it is evident that the students in classroom B had considerably stronger spatial visualization skills at the onset of the program. Classroom A's pre-test average was 59.2% and 13 out of the 22 students were identified in the low at-risk group (PSVT:R $\leq$ 70%) whereas the pre-test average for classroom B was 90.3% and only two out of the 20 started in the low performing group. There was a considerable increase in spatial visualization training effectiveness among students entering with low PSVT:R pre-test scores as shown by the Low Group students seeing the largest percent increase between pre- and post- tests (15.6%). A minimal increase or drop in scores is to be expected among students who start the class with high scores, due to the multiple-choice nature of the PSVT:R test. The last three rows of Table 2 show results for women in each class and overall. The women in classroom A seemed to have benefited more from the spatial visualization training as shown by their larger percent increase (16.7%) between their pre- and post- tests compared with all participants (6.3%) and low performing students of both sexes (15.6%).

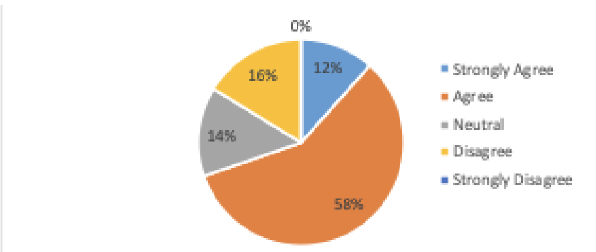
Table 2. Summary of Results on the PSVT:R Pre- and Post- Test

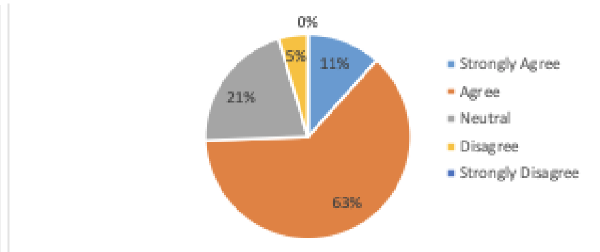
	Pre-Test Score	Pre-Test Percent	Post-Test Score	Post-Test Percent	Percent increase
All students in Classroom A (n = 22)	17.8	59.2%	20.9	69.7%	10.5%
All students in Classroom B (n = 20)	27.1	90.3%	27.6	92.0%	1.7%
All participants in study (n = 42)	22.2	74.0%	24.1	80.3%	6.3%
Classroom A Low Group ≤ 70% (n = 13)	13.4	44.6%	17.9	59.7%	15.1%
Classroom B Low Group ≤ 70% (n = 2)	19.5	65.0%	25.0	83.3%	18.3%
All Participants Low Group ≤ 70% (n = 15)	14.2	47.3%	18.9	62.9%	15.6%
Classroom A Women	14.7	48.9%	19.7	65.6%	16.7%
Classroom B Women	23.7	78.9%	26.0	86.7%	7.8%
All Women in study	20.7	68.9%	23.9	79.6%	10.7%

Upon evaluating the percentage of students who scored 70% or lower on the PSVT:R but then raised their PSVT:R to above this threshold, 55% of the low performing students in classroom A and 100% of the students in classroom B moved out of the at-risk category. Of the nine female participants, five started in the low group and three out of those five ended up moving out of this at-risk group.

In addition to the PSVT:R standardized test data, the responses to the survey administered to both classrooms were analyzed. Figure 1 shows the results of the questions that were based on a 5 point Likert scale. All of the students used the App with their smartphones except for two who used tablets. Students were asked their opinion whether they could complete assignments using a small phone screen size and 70% said they “strongly agree” or “agree” (Figure 1a). When asked whether the Spatial Vis App was a good use of their time, 74% said they “strongly agree” or “agree” (Figure 1b). The remaining Likert questions addressed whether students’ self-efficacy in their spatial visualization and sketching skills improved. 42% of students thought their spatial visualization skills were “very good” or “good” BEFORE using the Spatial Vis App (Figure 1c) while 91% of the students thought their spatial visualization skills were “very good” or “good” AFTER using the App (Figure 1d). For sketching, 47% of students felt their sketching skills were “very good” or “good” BEFORE using the App (Figure 1e), which increased to 88%

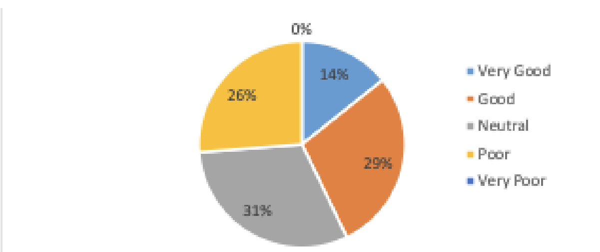
AFTER using the App (Figure 1f). The most challenging module for the students was Lesson 8: Rotations about 2 axes, while the easiest module for the students was Lesson 1: 2D Rotations.

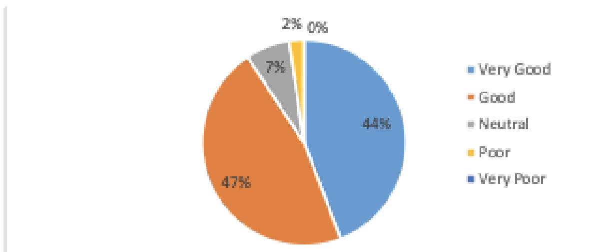




a. I could adequately complete my assignments given my device's screen size

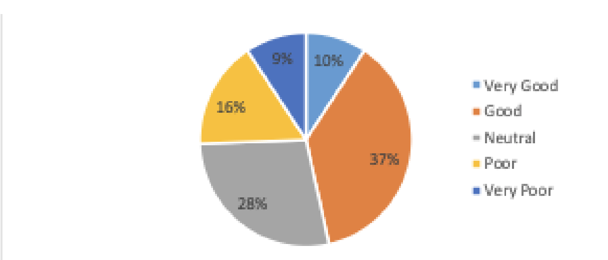
b. I feel like the Spatial Vis App was a good use of my time

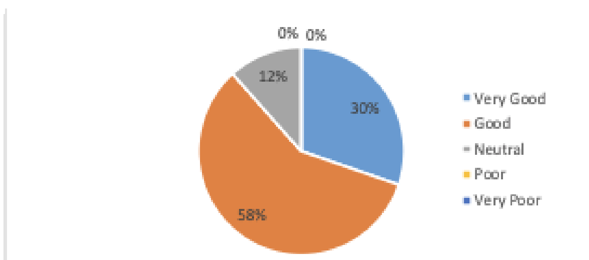




c. Student perception of spatial visualization skills before using Spatial Vis App

d. Student perception of Spatial Visualization skills AFTER using Spatial Vis App





e. Student perception of sketching skills before using Spatial Vis App

f. Student perception of sketching skills AFTER using Spatial Vis App

Figure 1. Summary of Survey Results on Likert Questions

3. Discussion and Limitations

Of interest was the large difference found in pre-test scores between classroom A and classroom B. In addition to the gender gap typically found in spatial skills between men and women, students of lower socioeconomic status, which is determined based on family's income, occupation and education, have been shown to perform more poorly in spatial activities than students of higher socioeconomic status [8]. These differences in spatial abilities have been thought to be due to less exposure to building toys, video games, and sketching. Participants in this evaluation were not asked questions about socioeconomic status, however, high school A has 28% of the student population on free or reduced lunch while high school B has 19%. A difference in socioeconomic status might explain the different pre- and post- test results for classroom A (59.2%), which were lower than classroom B (90.3%) but causality is not conclusive without more information. Other factors that call for further investigation include classroom B's week-long drafting lesson and some introduction to CAD prior to taking the pre-test that might have given them an edge. But what effect did classroom A's prior experience with engineering instruction though the schools' Career and Technical Education program (CTE) have on pre-test scores? In future work much more attention will be made to control for these types of variables.

The persistence metric (average stars) represents how often a student looks for hints or peeks. Upon reviewing the average stars for each study participant, it was observed that the students in classroom A were much less persistent (average stars in the class = 2.66) than the students in classroom B (average stars in the class = 2.9). Furthermore, the students who were in the low or at-risk group hinted and peeked much more often than those with stronger spatial skills. Of the 15 low performing students, five were flagged yellow representing average stars less than 2.78 and seven were flagged red representing average stars less than 2.55. This means only 3 of the low performing students were "persistent." In general, the students in low performing range who were more persistent performed better in their post-test scores. It was also interesting that several of the students who scored fairly well in the pre-test and who subsequently dropped in their post-test scores by more than one point were the ones that were not persistent in the App (average stars were flagged as low).

The text based questions in the survey indicated that the students enjoyed using the Spatial Vis App overall. Students felt it was helpful and allowed them to get practical skills through sketching instead of just theory, "I thought that it was a really well developed App, it was very educational, and really helped me a lot with 3 dimensional shapes since I started working with it." One student even indicated that it was "better than paper and pencil".

One of their favorite aspects of the App was that it was easy to use but they liked that the level of difficulty got more challenging as you progressed through the App, "I enjoyed the lessons greatly. The App's lessons were well structured in progression of difficulty and it was simple to use/navigate." Students enjoyed the immediate feedback and hints, "The feedback was a good feature. It showed what percent of lines were correct, incorrect, and the missing lines" and appreciated that they could retry assignments as many times as they wanted. They also liked the gamification (where they could try to maximize their stars) and several said, "It did not feel as if I was doing schoolwork but more like a game which I enjoyed." Students also indicated they liked the straight line feature that automatically straightened their line if they held it for a few seconds.

Furthermore, the students also appreciated the help resources accessible within the App, e.g., lecture videos and animations that describe how to complete each module, "I really liked how the creators included a video to help people with the lesson beforehand, something like that can really help out a person like myself, because I'm a visual learner."

Some students did not like the small screen size of the App while trying to work on a cell phone, “I would prefer more grid space to draw out the sketches,” and a few mentioned struggling with drawing the shapes, “It was really hard to draw things with my finger.” It seems using the App on a larger touch screen, like a tablet, or using a stylus would be preferable to alleviate these types of concerns. Furthermore, eGrove Education is currently developing a web-based version of the app to work on desktops and laptops with larger screen sizes which will be ready for the 2021-2022 academic year.

High school engineering teachers who participated in the evaluation had the following suggestions for App use in the high school classroom:

- Use the App prior to introducing any sketching or 3D design units
- On the first few units, introduce the lesson to the whole class and then use the rest of the class for students to work on the App. Then eventually move towards having students work at home on their own.
- Due periodic checks of students’ progress
- Highly recommend using the resources included with the App., hands-on activities and worksheets. These can be used either as an intro activity to a unit or as a post-assessment.
- Students will eventually diverge and work at different paces due to their proficiencies, that's OK. Allow the students to work ahead and watch the videos on their own before starting a unit.
- The Spatial Vis App can be taught as part of an online classroom, but it has its challenges. If the curriculum is fully online, have students send screenshots when asking for help. Meet with students individually for those who struggle at the beginning.
- Make sure teachers do the lessons either before or with the students.

This evaluation was not a controlled study and the classrooms that participated represent only two of the 35 high schools that offer this dual credit program with the University of Arizona, all of which vary considerably in socio-economic status, experience of instructors, and demographics of students. Participants in this evaluation had prior experience with engineering and engineering concepts which may have improved their pre-test scores and limited the amount of gains possible in their PSVT:R scores. Findings from this evaluation are to guide future improvements for the dual credit introduction to engineering course and are not necessarily generalizable to other populations.

4. Conclusion

The gamification of the Spatial Vis educational App encourages self regulated learning (SRL) though both intrinsic and extrinsic rewards as students improve their spatial visualization skills. Students always have their cell phones charged up and at hand. They enjoy their phone or tablet for social media and gaming, so it is naturally satisfying to do schoolwork using this format. It is also intrinsically rewarding for students to meet the challenge of solving the touchscreen puzzles in the App, as they get harder and harder. The addition of stars, “hints” and other game-like features in the Spatial Vis educational App add extrinsic motivation to the students’ SRL. These elements of the application make for a robust learning experience.

High School A and B both participate in a dual credit engineering course and are part of a 35 high school program. After the spatial visualization application course was completed the mean score for the participant group improved by 6.3% and students who were classified in the at risk low performing group and had a pre-test of 70% or lower improved on their post-test score by 15.6%. Additionally, female students improved their post-test score on average by 10.7%. Importantly, student self efficacy improved after treatment completion, as was demonstrated in the student evaluation survey responses. Due to the positive results found in the qualitative and quantitative data from this small evaluation, additional schools will be encouraged to use the spatial visualization application in the future, particularly for students who score lower than 70% on the PSVT:R assessment.

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