

Freehand Sketching on Smartphones for Teaching Spatial Visualization

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Abstract

Mobile devices are becoming a more common part of the education experience. Students can access their devices at any time to perform assignments or review material. Mobile apps can have the added advantage of being able to automatically grade student work and provide instantaneous feedback. However, numerous challenges remain in implementing effective mobile educational apps. One challenge is the small screen size of smartphones, which was a concern for a spatial visualization training app where students sketch isometric and orthographic drawings. This app was originally developed for iPads, but the wide prevalence of smartphones led to porting the software to iPhone and Android phones. The sketching assignments on a smartphone screen required more frequent zooming and panning, and one of the hypotheses of this study was that the educational effectiveness on smartphones was the same as on the larger screen sizes using iPad tablets. The Spatial Vis™ mobile sketching app was implemented in a college freshman engineering graphics course to teach students how to sketch orthographic and isometric assignments. The app provides automatic grading and hint feedback to help students when they are stuck. Students were administered a pre- and post- spatial visualization test (PSVT-R, a reliable, well-validated instrument) to assess learning gains. The trial analysis focused on students who entered the course with limited spatial visualization experience as identified based on a score of $\leq 70\%$ on the PSVT-R since students entering college with low PSVT-R scores are at higher risk of dropping out of STEM majors. Among these low-performing students, those who used the app showed significant progress: (85%) raised their test scores above 70% bringing them out of the at-risk range for dropping out of engineering. In addition to the PSVT-R instrument, a survey was conducted to evaluate student usage and their impressions of the app. Students found the app engaging, easy to use, and something they would do whenever they had “a free moment”. 95% of the students recommended the app to a friend if they are struggling with spatial visualization skills. This paper will describe the implementation of the mobile Spatial Vis™ sketching app in a large college classroom and highlight the app’s impact in increasing self-efficacy in spatial visualization and sketching despite the small screen size.

Introduction

The use of mobile devices and specifically touchscreen technology in education has increased tremendously over the years due to their increase in ubiquity and computing capabilities. A survey was conducted online within the United States by Harris Poll on behalf of Pearson in 2015 [1] and found that Tablet usage remains high and growing – especially for younger students at 78% (66% usage of laptops). At lower grades elementary school iPads are common, but Chromebooks are becoming more popular [1]. Chromebooks can be purchased with or without touch screens, but in the coming years it is anticipated that touchscreens will become more popular [2]. Smartphone usage has increased across all grade levels and is most prevalent among older students. In 2015, 53% of elementary school students, 66% of middle school students and 82% of high school students used smartphones in school regularly. The availability of smartphones in Higher Ed has increased from 84% in a 2014 [3] to close to 100% in a 2017

study, and many 7-12th grade schools have initiated a Bring Your Own Device (BYOD) policy [4].

Mobile devices provide an opportunity for higher engagement, enhanced student understanding and allow students to learn beyond the classroom. Smartphones also provide an easy way for teachers to encourage students to learn how to responsibly participate in the digital world [5]. They also have an advantage of being able to automatically grade student work and provide instantaneous feedback. Furthermore, the latest “intelligent” tutoring systems are able to evaluate a student’s areas of limitations, but also identify why students are making specific errors [6]. These innovations allow teachers to track weaker students and intervene appropriately. There are now hundreds of applications that can effectively expose children to important foundational skills [7]. However, numerous challenges remain in implementing effective mobile educational apps and there is little evidence that digital learning can be implemented at scale in a way that improves outcomes for disadvantaged students [7]. Furthermore, although cell phones can be effective in the classroom as a learning tool, the inappropriate use of mobile devices can create distractions in the classroom that are detrimental to learning [8]. In this study, an educational app was developed for use on smartphones outside the classroom as homework.

One foundational skill that has been shown to be especially beneficial for women and other underrepresented minorities in STEM is Spatial Visualization **Error! Reference source not found..** Spatial Visualization (SV) refers to the ability to manipulate geometric shapes in one’s mind and is important in many STEM fields ([9] and [11]). A seminal study by Sorby **Error! Reference source not found.** showed that SV skills are learnable, and a single course using freehand sketching on paper has been demonstrated to improve SV skills. Sorby’s study at Michigan Tech from 1993 to 2012 with over 7,000 students showed how graduation rates in engineering were significantly increased due to SV training **Error! Reference source not found..**

Furthermore, there is a large body of evidence that indicates self-efficacy, or an individual’s belief in his or her competence to perform activities necessary to produce specific performance achievements, is a huge predictor of performance and motivation in education ([12] and [15]). Bandura [15] advocates that what an individual believes, rather than what is factually true, is a stronger indicator of performance, motivation and well-being. These self-evaluations affect all aspects of human experience including what goals people strive for, the amount of effort expended to achieve these goals, and the possibility of accomplishing certain levels of behavioral performance [16]. Bandura indicates that the most effective way of developing self-efficacy is through mastery experiences. As students perform a task successfully, their belief in their own competence strengthens. But if students do not adequately deal with challenging tasks then their self-efficacy is weakened.

Self-efficacy, which is a critical component in task performance and motivation, coupled with the correlation between spatial visualization skills and success in a number of STEM disciplines suggests that research is needed to study spatial ability through the lens of self-efficacy ([17] and [18]). Towle, et al. [17] examined whether spatial ability has a correlation to self-efficacy, using the Purdue Spatial Visualization Test-Visualization of Rotations (PSVT:R) test and a self-efficacy assessment developed specifically for their study. Their results showed that there was a strong

correlation between self-efficacy and spatial ability. Another study found similar results, which indicates that fostering students' belief that their spatial ability can be developed could be a significant pedagogical approach to developing these skills and consequently increasing capabilities within STEM education [19]. Minear, et al., [20] explored the relationship between spatial ability and self-efficacy (two predictors of engineering success) and found spatial ability was correlated with multiple forms of engineering self-efficacy in less experienced, but not more experienced engineering students.

A spatial visualization app was developed by eGrove Education, Inc. **Error! Reference source not found.** to make use of the prevalence of touchscreen devices in education and to make SV training more engaging and easier to teach. Motivated by Sorby's finding that the "importance of sketching in developing 3-D spatial skills cannot be understated" **Error! Reference source not found.** the app enables students to freehand sketch assignments on a touchscreen. Sketching provides an added benefit beyond SV, and has been correlated to communication, teamwork, and creativity [19]. The app runs on iOS and Android devices (see Figure 1). Students sketch isometric and orthographic assignments which are automatically graded. Students can attempt an assignment as many times as they need, take a hint with stuck, or peek at the solution. Prior studies with the Spatial Vis™ app have demonstrated its effectiveness ([21] through [26]). In these studies, students worked on the app in class or as homework using iPads with large screen sizes as their device.



Figure 1: Spatial Vis™ App available on Apple and Android Phones and Tablets

Although there has been significant research assessing user experience with technology devices, very little research has been conducted in investigating if users are affected by specific mobile device characteristics such as screen size [27]. Most research to date has been based off of desktop screen sizes. But some reports have shown that there is a significant effect of mobile phones' screen size on efficiency in information seeking tasks and observed that participants who used larger screens were more efficient. However, the magnitude of the effect is related to the nature of the task. Tasks that are not easy and require a significant amount of low-level interactions (such as scrolling) seem to greatly benefit by the additional screen area. Despite large differences on task completion times, in a particular study [27] the task completion rates were almost equivalent. This finding suggests that differences on screen size did not impact effectiveness [27] and [28].

For spatial visualization training, going digital is beneficial in providing students with flexibility as to when and where they perform the sketching assignments. Furthermore, students who need more time to complete their sketching assignments can do so at their convenience. The Spatial Vis™ app was originally developed for iPads, but the wide prevalence of smartphones led to porting the software to iPhone and Android phones. One concern for this migration to smartphones is the ease of sketching isometric and orthographic, which require more frequent zooming and panning drawings on smaller screen sizes.

To assess whether screen size impacts the efficacy of the Spatial Vis™ mobile sketching app, the app was used in a college freshman engineering graphics course to teach students how to sketch orthographic and isometric assignments. A hypothesis of the study was that the educational effectiveness on smartphones was the same as on the larger screen sizes using iPad tablets. Students were administered a pre- and post- spatial visualization test (PSVT-R, a reliable, well-validated instrument) to assess learning gains. The trial analysis focused on students who entered the course with limited spatial visualization experience as identified based on a score of $\leq 70\%$ on the PSVT:R since students entering college with low PSVT:R scores are at higher risk of dropping out of STEM majors.

This paper describes the implementation of the spatial visualization sketching app in a large college classroom using students' personal mobile devices and highlights the app's impact in increasing self-efficacy in spatial visualization and sketching.

Pilot implementation in First Year Engineering Graphics Course

The Spatial Vis™ mobile sketching app was implemented in a college freshman engineering graphics course to teach students how to sketch orthographic and isometric assignments. This class was one of the first to use the spatial visualization training app on students' smartphones to study if the experience was the same as on larger screen sizes using iPad tablets.

Students were assigned sketching problems as homework using their personal devices of which 60.5% were Apple iPhone, 13.7% were Apple iPad, 24% were Android phone, and 1.6% were Android tablet. Students were administered a pre- and post- spatial visualization test (PSVT-R, a reliable, well-validated instrument) to assess learning gains. In addition to the PSVT-R

instrument, a survey was conducted to evaluate student usage and their impressions of the app. There were 131 students in the class who completed all of the assessments, of which 41 were identified in the low performing range based on the PSVT:R pre-test administered. Preliminary results of the study are summarized below.

Results

An emphasis of the analysis for the trial described in this paper was how beneficial the SV training was for students who entered college with low PSVT:R scores and whether screen size affected performance. Sorby's data showed that students who entered as engineering freshmen with PSVT:Rs equal to or lower than 60%, but who took an SV training course, significantly increased their graduation rates. The data also showed that students with incoming PSVT:R scores between 60% and 70% would also benefit from SV training, since students with over 70% scores had higher graduation rates **Error! Reference source not found..** The NSF sponsored Engage Engineering website [29] indicates a threshold of 60% or 70% would be appropriate for additional SV training. In our analysis, we adopt the 70% threshold ($\leq 70\%$) as an indicator that a student has low SV skills and is "at risk" of dropping out of STEM due to SV abilities [26].

We classified successful SV training as whether a student, who's pre-test score put them in the at-risk category ($\leq 70\%$), moved out of this category ($>70\%$ on PSVT:R post-test) after the SV training. The effectiveness of SV training can then be measured by the percentage of students who enter with PSVT:R scores $\leq 70\%$ but then have post-test scores $> 70\%$. Results for the trial described in this study (spring 2018, $n=131$) that allowed students to use their own smartphones are compared to two prior trials. The trial in winter 2017 was in an elective class for aerospace and mechanical engineering students ($n=32$) where all student work was completed during scheduled lab sessions using provided iPads with a tutor available for help. The trial in spring 2017 was in a required structural engineering course ($n=79$) in which the assignments were done as homework using iPads that were checked out from a maker studio. Table 1 shows the number of students who entered each of the trial courses with SV scores that put them in the "at risk" category ($\leq 70\%$) and the percentage of students who completed the course with SV scores above that category.

Table 1: Low Pre-Test Students (PSVT:R $\leq 70\%$)

Course	Average Pre-Test Score	Average Post-Test Score	Average % Increase between Pre- and Post-	Students that moved out of Low Pre-Test Group (Post-Test above 70%)
MAE 7 Winter 2017 ($n=11$), <i>elective</i>	61%	80%	31%	82%
SE 3 Spring 2017 ($n=27$), <i>required</i>	57%	75%	31.5%	67%
SE 3 Spring 2018 ($n=41$), <i>required</i>	57%	76%	33%	85%

As seen in Table 1, there was a significant increase in SV training effectiveness among students entering with low pre-test scores. The percentage of students who moved out of the low pre-test

group was 82% in the Winter 2017 elective class (a 31% average increase in scores). The percentage dropped to 67% in the Spring 2017 required class, but it is to be expected that an elective class would have higher gains than a required class since students taking the elective would be more motivated for self-improvement. However, these students still saw an average increase in PSVT:R scores of 31.5%. The percentage in the current study when students used their own devices with smaller screen sizes was as effective as the prior studies using iPads (85% of the low performing students moved out of the at-risk category and saw a 33% average increase in their PSVT:R scores). The fact that both the elective and required classes had high rates of effectiveness indicates that the possible self-selection bias of the elective class is small. In addition, students in the required classes in Spring 2017 and Spring 2018 used the SV training app for homework, which is an indication of the effectiveness of the app as a tool for self-guided learning.

Because the data from the app is digitized, it enables the instructor to see the usage and behavior of students such as the number of hints and peeks they take on each assignment which corresponds to the number of stars earned. This allows the instructor to observe the persistence of students as well as identify assignments that appear to be difficult for the students (because they take more hints and peeks to complete). Furthermore, the instructor has access to the images of each sketch submitted so they can better understand the student's thought process. This detailed data is still being analyzed and will be reported in more detail in the final paper.

A post survey using google forms with open ended and questions using a 10-point Likert scale was conducted to evaluate students' perceptions of the app and their self-efficacy in spatial visualization and sketching skills. When asked when students used the app, many said they mostly did it during their free time while watching television, doing laundry, hanging out at home, while on the bus, and even in the restroom. One student said, "Most of my work was done when I had a 30-minute break between classes, it was easier to do than other work since I didn't need to find a table to set my stuff up."

The average overall impression of the app was 8.45 out of 10, and 95.2% said they would recommend the app to others with low SV skills. In terms of device screen size, 69% of the students ranked the ability to adequately complete assignments an 8 out of 10 or above. The entire class average related to screen size was 8.1. Only 10% of the students said that their least favorite aspect of the app was screen size/navigation related, providing comments such as "my screen was sometimes too small, so I had to zoom in and out a lot and accidentally drew/erased where I didn't want to."

Table 2 shows a comparison of self-efficacy related to spatial visualization and sketching skills.

Table 2: Self-Efficacy related to Spatial Visualization and Sketching Skills

Skill	Before using App	After using App
Spatial Visualization	64.5% Good/Very Good 16.9% Poor/Very Poor	89.4% Good/Very Good 0% Poor/Very Poor
Sketching	64.5% Good/Very Good 18.5% Poor/Very Poor	85.5% Good/Very Good 0% Poor/Very Poor

When asked what was their primary motivation for completing the exercises in the app, 78.2% completed the app because it was a required part of the grade, 25% said they were competitive and wanted to earn more stars than their peers, 66.9% wanted to do more to earn extra credit in the course, 54% said they did it because the app was fun and addictive. Some of students' favorite aspects of app were that it encouraged the user to not give up by giving them an incentive (stars), it was on their phones and easy to use, it was like solving puzzles, they enjoyed sketching, and it helped them improve in an area that they would have never even thought about improving on. Furthermore, they thought the app had a good balance of easy and hard questions, the user interface was nice and easy to use with the grid lines, and that the app clearly showed if they were correct or not.

Students were assigned to do half of the available exercises in each chapter (~15 per module). Only 21% of the students thought that the number of exercises assigned in each chapter were too many. 69.4% of the students thought that the rotations about two axes was the hardest lesson because it was challenging for them to visualize two different kinds of rotation in their minds without seeing each step. While 89.6% of the students said the app usually or always graded the sketches accurately, probably the most common suggestion for improvements to the app was to relax the grading algorithm and make the grading of hidden lines more flexible.

Conclusions

Overall students enjoyed using the app and provided constructive criticism in its implementation. While a few commented that the screen size was challenging for them to effectively sketch their solutions, the overall gains in PSVT:R pre and post-tests, especially for the low performing students at risk for retention in STEM show that students using their personal smartphone devices improved at a similar rate than other classes where the app was done on larger screen sizes (e.g., iPad). However, as a designer of the app, it is important that specific design decisions be made for small screens to increase their efficiency [27] and efforts will be made to investigate alternative panning and zooming capabilities to facilitate better navigation during the sketching exercises. Screen size does matter. While bigger screen sizes can lead to more efficiency for a variety of touchscreen activities, at some point a larger screen sizes ultimately reduces portability of the device. One future direction could be the study of the screen size effect over time, as the familiarity with a device and an application increase. We will continue to evaluate methods to improve efficiency and ease of use for small screens in the app.

We also received very constructive feedback from the students on features that will make the app better. Students requested a Windows version to work on Surface Pros and other window touchscreen devices, adding a snap to grid line feature to make sketching easier, and providing more meaningful hints such as "you are missing one line". The meaningful mini hints are something that has since been implemented into the app and is being reported on in a companion ASEE paper **Error! Reference source not found..** Other suggestions included the use of more interesting shapes and more challenging assignments and providing a mechanism to tell you what problem you are working on, what has been completed and how many you still have to accomplish.

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