Full Paper: Implementing Classroom-Scale Virtual Reality into a Freshman Engineering Visuospatial Skills Course

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Abstract

In this study, our team developed a virtual reality (VR) integrated curriculum for a freshman engineering visuospatial thinking course. Visuospatial skills, especially understanding how a 2D image represents a 3D object, are known to be an important part of student success in engineering. To ensure a minimum level of visuospatial skills in later courses, the Ohio State University offers a course on visuospatial thinking for incoming engineering freshmen; it is required for students that score below 18/30 on the Purdue Spatial Visualization Test: Visualization of Rotations (PSVT:R). To help these students interrelate 2D images and 3D representations, we created a set of collaborative and analytical activities that the students engaged in with the help of VR technology. For this, we built custom smartphone VR applications for several of the modules in the Developing Spatial Thinking workbook by Sheryl Sorby (ISBN 978-1-111-13906-3). Using hardware supplied by us (Google Cardboard headsets and smartphones), students completed VR activities in pairs (or groups of 3). Each partner had a turn with the VR application and communicated with their non-VR partner to complete interactive visuospatial problems. We evaluated progress using pre- and post-module quizzes, and gains were significantly higher when students were given the experimental VR instruction than when they were not. Students were also interviewed at the beginning and end of the course, explaining their thinking as they worked visuospatial problems. By using this smartphone-based approach, we were able to implement a VR intervention on the classroom-scale, with each student having simultaneous access to the VR content.

Introduction

Visuospatial skills have been shown to be a crucial predictor of success of students in STEM [1]–[5]. However, not every incoming engineering freshman excels in these skills, and there is a gender and racial gap in students' performance on visuospatial tasks [5]–[8]. Fortunately, visuospatial skills can be explicitly taught [1], [5], [9]–[11]; research shows that when students who struggle in this area take a freshman-level course in visuospatial thinking, they have measurably better performance throughout their college career than those who do not [12], [13]. Additionally, training can lead to significant improvements in visuospatial skills that persist in time and can translate to other tasks [1], [10], [11].

For these reasons, the Ohio State University (OSU) offers a visuospatial skills course aimed at incoming freshman engineering students with relatively weak visuospatial skills. Related strategies are in place at multiple other universities [14]. At OSU, all incoming engineering students are given the Purdue Spatial Visualization Test: Visualization of Rotations (PSVT:R), and students who score below score below 18/30 are required to take the course. These students are the majority of those enrolled in the course, though students with higher scores may opt to take the course, and a small number of students from the College of Dentistry take the course as well as a requirement for their major. In this work, we describe controlled implementation of recently developed virtual-reality (VR) modules in the visuospatial thinking course. These modules are designed to help bridge the gap between the 2D representations of 3D phenomena and the 3D models that students must have in their mind in order to understand them.

Many prior studies have described the application of VR interventions in various STEM classes, with varying degrees of success. There is evidence that students given VR interventions report being more engaged with the material or having a better conceptual understanding than control students, but it is not clear that these interventions lead to gains in measured learning outcomes, and these interventions often rely on expensive specialized hardware [15]–[23]. Regarding VR-augmented spatial-thinking training specifically, some studies reported the VR augmentation to have a significant effect on learning outcomes, while others found no effect, a very moderate effect, or an effect only on certain tasks [24]–[27]. In a related study in the context of computation, Hundhausen et al. in [28] analyzed 24 experimental studies on effectiveness of different visualizations of computer algorithms. They found that how students used visualizations was more important than what the visualizations actually displayed. Translating this to the engineering context, when visualizations are used in a passive way (for example, students only look at a 3D representation or simply rotate it around), the effect of 3D visualizations is not significantly different from other forms of visual or text materials. However, when students actively engage with the 3D materials and platform, for instance by using the technology as part of the problem-solving process and to actively develop personal projects, the tools are shown to be more effective. This is also consistent with the more recent findings of improved learning gains in calculus through the use of VR in student projects [29]. Finally, there is some indication that learning gains through VR may depend on a student's prior experience with visuospatial rotations in an electronic or gaming context [30], suggesting that comfort with the technology is a non-negligible factor. The strong dependence of the effectiveness of these interventions on exactly how they are implemented is expected based on research on innovative learning technologies in general. Specifically, research has consistently shown that technology by itself does not do much to enhance students' learning if it is not integrated in the classroom based on sound educational theories [27], [31].

We aimed to ensure student engagement and learning by promoting self-efficacy, one's belief that one can successfully complete a specific task [32], [33], because it helps determine whether students engage with tasks, persist when they face difficulties, and finish tasks. Mastery experiences (actually performing a task and succeeding) can increase self-efficacy [34], especially when they are built on achieving proximal goals - smaller tasks that are almost guaranteed to be completed successfully. Since self-efficacy is domain-specific [35], we hypothesized that low visuospatial self-efficacy could be one of the main reasons of why students disengage with visuospatial tasks. According to the self-efficacy theory, visuospatial self-efficacy can be increased by providing students with small, manageable learning goals that they can accomplish, and provide multiple opportunities for engaging in this type of experience. In the current intervention, we incorporated this principle by spreading the intervention sessions over the course of the semester and providing students with tasks that build on each other, are manageable, are not graded, and often are aimed at developing students' thinking and problem strategies rather than getting at the correct answer.

Methods

The study was conducted in the fall of 2018 with a total initial enrollment of $N = 80$ students split between three sections of the course. The data were collected for only 71 students due to some students not consenting to participate in the study and some being under 18 years old. These sections were split into the control group ($n = 23$), and the experimental group ($n = 48$). The experimental group included two course sections, and the control group was one course section. All course sections were taught on the same day by the same instructor. The intervention activities were incorporated as part of the class curriculum in the treatment sections, while the control section was business-as-usual.

We implemented the intervention in 5 of the 10 modules of the course textbook [36], [37]: Surfaces and Solids of Revolution, Combining Solid Objects, Rotation of Objects about a Single Axis, Rotation of Objects about Two or More Axes, and Cutting Planes and Cross Sections. The decision to include these modules was based on the mutual agreement with the instructor; if the module was heavily drawing-based, not possible to implement in VR with available resources, or better implemented with real-life objects, such modules were not treated with VR. The five modules listed above which were treated with VR were heavily three-dimensional, involved minimal drawing, and were ideal candidates for VR treatment. Each of these five modules had a corresponding smartphone app (except the rotation modules, in which the apps could be configured to work with either module) and an activity sheet, which the students worked on with a partner or in small groups during class. Each app used a Google Cardboard equivalent headset for stereoscopic VR (see Figure 1C), and students interacted with the app using a Bluetooth controller. The VR apps were developed in the Unity game development platform [38]. Additionally, students were able to interact with the app by moving their head; in most cases doing so causes the object in focus to rotate the same amount, allowing the student to view the object from all sides.

Here we describe only two modules in detail; the remaining modules will be outlined in a future publication. In the Surfaces and Solids of Revolution app, students were able to choose a 2D shape or create an arbitrary one (see Figure 1A), then use this shape to create a solid of revolution by interactively choosing the axis of rotation, the distance from the axis to the shape, and the amount of rotation (see Figure 1B). Activities for this module instructed students to create their own 2D cross-sections and axis, and challenge a partner to predict the corresponding surface of revolution.

In the Cutting Planes and Cross Sections app, students choose a 3D object from a menu and were able to move a plane through the object and view the cross section created. They are also able to remove the part of the object to one side of the plane in order to see how the cross section is oriented in 3D space (see Figure 1C). The activities in this module had students challenging one another to find the correct 3D object(s) to create the same cross section.

We had three primary tools to measure the effectiveness of the intervention. First, since each week of class covered one module from the Developing Spatial Thinking workbook, we created pre- and post quizzes for these modules, taken the week before and the week after the module was covered respectively. Each quiz was five questions long. Although questions were not typically identical on the post- and pre-quizzes, they were trivial alterations such as swapping a rectangular cross-section for a triangular one. Second, all the students take the PSVT:R either before coming to OSU (primarily freshman engineering majors) or at the beginning of the course (primarily dental students), and the PSVT:R is used as a final exam for the course. Finally, we conducted optional interviews with a subset of students (*N* = 26) in the first and final few weeks of the course. During these interviews, students were asked to complete several open-ended visuospatial tasks while explaining their reasoning, with a 3-minute limit for each task and no assistance from the interviewers. At the end of the second interview, students were also debriefed about the course. Interview tasks were created based on the textbook topics to cover all of the modules.

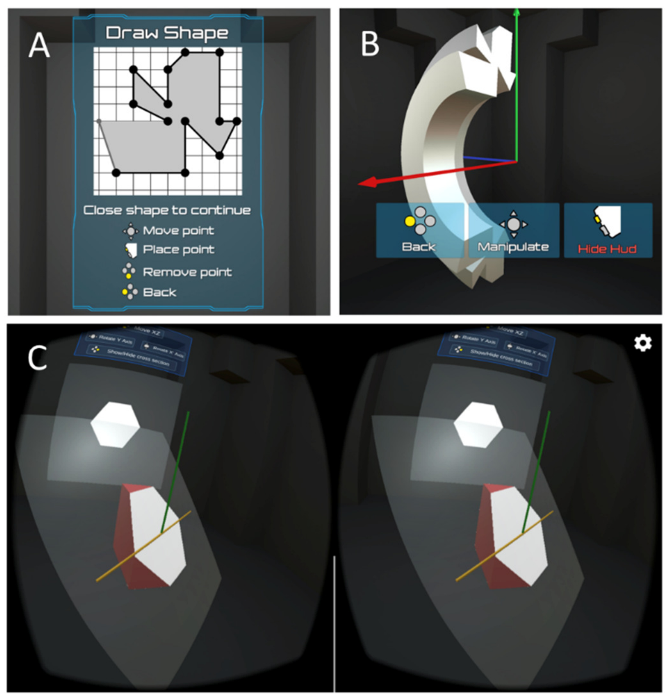

Figure 1: Screenshots of the apps for (A,B) the Surfaces and Solids of Revolution module, and (C) the Cutting Planes and Cross Sections module. Panel (C) shows what is displayed on the screen when the app is run on a smartphone in stereoscopic VR.

Results

On the Purdue Visuospatial Rotations Test, the treatment group improved from a score of 17.1 out of 30 to a score of 24.3. The control group had a slightly lower pretest score of 15.4, but achieved the same final score of 24.3, on average. These averages are shown in Figure 2. The slight differences were not statistically significant, as determined by a repeated measures analysis using treatment as a between-subjects factor performed in IBM's Statistics Package for Social Sciences (SPSS). There was also no significant difference between the gains for males and females. It must be reiterated here that *N* is relatively small, and this is only made worse by splitting groups according to sex. Further study will be required to definitively address possible effects on PSVT:R for males and females.

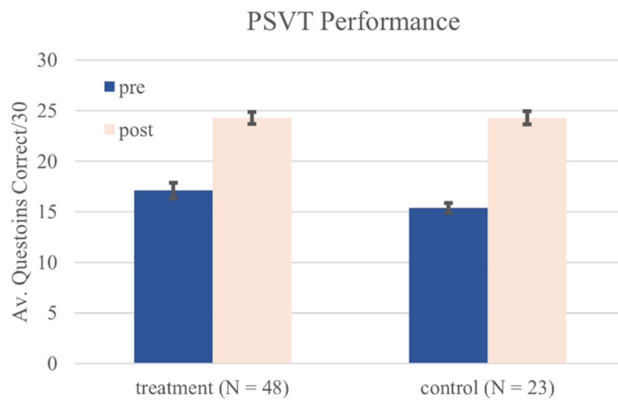

Figure 2: Average pre- and post-test student scores on the Purdue Spatial Visualizations Test for rotations for treatment and control groups.

The topic-specific weekly quizzes provide more granular data on the VR intervention. Clustering all quizzes together, we can compare the pre- and post-quiz scores for the treatment and control groups. Figure 3A shows that the gains from pre to post were almost indistinguishable for the two groups. The control group scored slightly lower on the pre-quizzes (49% compared to 52% for the treatment group), and the post-quiz scores were 83% for both the treatment and control groups. The difference in gains was not statistically significant

The analysis corresponding to Figure 3A grouped all quiz scores for the treatment group together, even though not all quizzes had a corresponding VR treatment. Alternatively, we could cluster all quizzes for which a student received a VR treatment together, and all those quizzes for which there was no VR treatment. That is, we combine all the control group quiz scores with the

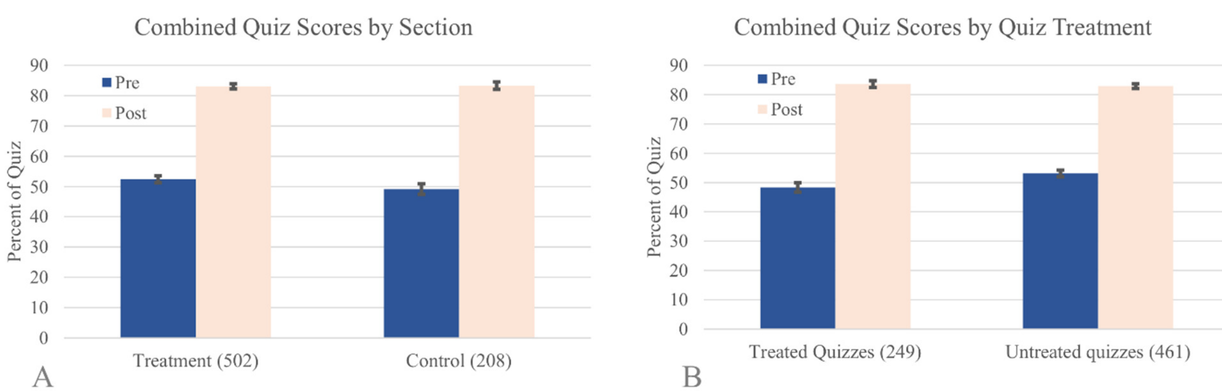

Figure 3: Results of weekly quizzes for treatment and control groups. (A) The scores on pre- and post-quizzes split up by treatment and control classes. (B) Scores divided according to whether a particular quiz topic was treated using VR. Error bars represent standard error.

scores of the treatment group on quizzes for which no VR treatment was developed. The result of this analysis is shown in Figure 3B.

The gains are again very similar: 35.2% for treated quizzes and 29.7% for untreated quizzes. Because of the large number of quizzes being combined, the small difference is statistically significant with $p = 0.01$, as determined by a repeated measures analysis in SPSS using treatment as a between-subjects factor. The effect size is described by a Cohen's d of 0.27. Again, there was no significant difference in the gains for males compared to females. Although the number of quizzes in each group is large, the number of students participating is still low, particularly in the control group. These results should also only be taken as preliminary findings worthy of further study.

Although the VR treatments appear to have been effective in an overall sense, the effectiveness was somewhat inconsistent as measured by gains on weekly quizzes. In fact, in the 10th week, the control group actually had statistically significantly higher gains than the treatment group on the quiz covering Cutting Planes and Cross Sections. At that point in the semester, we observed that many of the students were not using the apps in stereoscopic VR; instead, they had the phone outside the headset to view it. One possible explanation for this is that, in the interviews, several students reported motion sickness when using the VR apps, and limiting the time that each student uses the app in stereoscopic VR might mitigate this issue [39], [40]. Additionally, since it was a pilot study, the materials tested were not yet refined, and some students noted that they found activities confusing and the Bluetooth controllers hard to pair with the smartphones. Future iterations of the apps and activities will be streamlined based on student feedback.

The interviews are currently being analyzed to identify what problem-solving strategies students used and how they change over the course of the semester. The preliminary analysis shows that students in the experimental condition had fewer difficulties in solving the visuospatial problems and verbalizing their reasoning at the Time 2 interview than those in the control condition. They also used more precise vocabulary to describe their thinking.

Since the intervention emphasized open-ended problem-solving and verbalizing one's visuospatial reasoning, the students may have improved in these aspects, but this improvement did not lead to a significant increase in formal test-based assessments. We will explore this question in more detail in a separate paper.

Conclusion

Given that the usefulness of technological interventions relies on how they are applied, we believe it is important to consider technology such as VR as a tool to achieve specific educational objectives rather than a driving force in making curricular decisions. To implement VR-infused curricula effectively, we needed to directly include students' engagement in the design of our VR materials. Our approach differs from prior work in that the VR-interventions have students actively interacting with that content, in addition to viewing it in stereoscopic VR. We found that VR can be an effective tool in aid of teaching visuospatial skills, as the increased gains on quizzes where a VR intervention was done were statistically significant, if small. We have also shown that classroom-scale VR on smartphones is a workable and effective teaching tool. We did hit a few roadblocks along the way due to the exploratory nature of this pilot study. In particular, it was sometimes difficult to pair the controllers to the smartphones in a classroom full of them, and some of the activities appeared to be confusing to students. We will keep developing these tools and refining them to further the understanding in the VR integration in STEM education and the pathways to improving students' visuospatial achievement, self-efficacy and problem-solving strategies.

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