Paper ID #18311

Work in Progress: A Study of Augmented Reality for the Development of Spatial Reasoning Ability

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Using Augmented Reality to Develop Mental Rotation Abilities

Spatial ability is recognized as an important predictor for student success in STEM fields (Sorby & Baartmans, 2000; Sorby, Casey, Veurink, & Dulaney, 2013). As such, identifying and implementing strategies that can reliably and significantly help students develop these abilities would be very valuable. Many different strategies have been employed as means for helping students develop these skills (Ha & Fang, 2016). Of particular interest is their description of two kinds of models that might be used for spatial training: tangible models and virtual models. Tangible models are physical objects, such as blocks, that can be used as aids for learning (Casey, Pezaris, & Bassi, 2012). Virtual models, according to their description, include computer-based animations and simulations, augmented reality tools, and virtual reality tools. And of course, sometimes both tangible models and virtual models are used in tandem.

Augmented reality (AR) involves the integration of virtual 3-D objects into a real 3-D environment (Azuma, 1997). One way to understand the range of ways to implement AR is to consider where the integration of the virtual and the real environments is displayed: on a fixed monitor, on a head-mounted device, or on a handheld device.

Figure 1: Fixed-monitor augmented reality

In this first category of using a fixed monitor, Contero, Gomis, Naya, Albert, and Martin-Gutierrez (2012) report on the use of "desktop augmented reality" exercise to improve spatial ability among engineering students. Figure 1 shows a marker on the desk that is in the view of the webcam mounted at the top of the monitor. The monitor then displays a top view of the desk (note the user's hand) along with a virtual 3-D object that appears in place of the marker. They described this approach to augmented reality as essentially being a replacement for typical mouse-based control of a simulation. While they did not directly compare this approach to a more traditional approach, they concluded that their short course (16 hours over 2 weeks), which included this technology, did in fact lead to growth in spatial reasoning ability, and that students were positive about using this technology.


Figure 2: Head-mounted augmented reality

In the second category of using head-mounted virtual reality, Dünser, Steinbügl, Kaufmann, and Glück (2006) report on their use of Construct3D, as shown in Figure 2. Users control the virtual objects by moving their hands much as they would if the objects were physically present. While they found some interesting differences between men and women, as well as differences based on one's prior training and experience with spatial reasoning, they did not find a statistically significant benefit from the use of their augmented reality tool.

The third category makes use of handheld devices to represent the augmentation. That is the approach we employed, and the app is described further below (see Figures 3 and 4). In short, the device is pointed at a physical marker in one's own physical space, and on the display of the device appears a mixture of the camera view and a 3-D object augmented on that camera view. Interaction with that object is then essentially just like pointing a camera, meaning that as you move the camera, the augmented object appears to stay fixed in space, allowing the user to walk around the object to see its various sides. In addition, the user can move the physical marker, and the object moves in space as if tied directly to that physical marker. The object can then also be manipulated by commands on the device, allowing for rotation of the object in a way that fits standard engineering practice (that is, rotation by 90 degree increments on the 3 major axes).

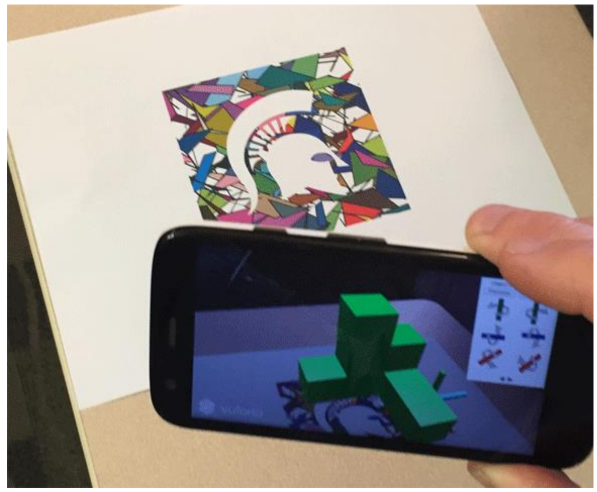
Figure 3: Handheld augmented reality

When comparing these three models, it would seem that a head-mounted augmented reality has significant advantages: it provides a larger field of view of the virtual objects, it does not have a boundary that separates the virtual objects from the real environment, and it allows for very natural control of one's view by simply turning one's head. The biggest disadvantage, and it is a very significant issue, is the cost of these devices.

While the fixed monitor solution is attractive because it can easily and inexpensively be added to existing computers, there is real question as to whether or not students actually see it as augmented reality or as an integration of a view of their own reality into a computer simulation.

Using handheld devices promises an interesting mix of affordability and scalability while potentially retaining perhaps the most compelling aspect of head-mounted virtual reality, which is direct manipulation. As described by Hutchins, Hollan, and Norman (1985), reducing the "gulf of execution" and the "gulf of evaluation" is expected to increase the "feeling of directness." When it is used, the ability to move a handheld device just like someone might move a camera is expected to be nearly automatic (execution) while seeing the 3-D object integrated with one's physical space via the camera view is expect to very similar to how one generally sees the world (evaluation). In the words of Hutchins, et al., the hope is that there would be a "qualitative feeling that one is directly engaged with control of the objects" rather than controlling a program that controls those objects.

Our approach

We decided to explore the handheld device approach for several reasons. Very significantly, no additional hardware was needed, as long as users have a smartphone or tablet computing device.

It also retains the flexibility of the head-mounted approach since students can physically move so as to change their view of the integrated virtual and real environment.

This study tested the use of handheld augmented reality on smartphone and mobile tablet devices for developing spatial reasoning (see Figure 3). The app allowed students both to move physically around a fiducial marker in order to view virtual objects from multiple angles (in addition to moving the paper marker). They also had the ability to rotate the objects along each of the major axes. It was reasoned that combining the constraints possible with a digital tool (such as doing exactly 90-degree rotations exactly on particular axes) with the realism of augmented reality would provide a new way for students to practice spatial reasoning tasks.

Games were also implemented in the app to support prediction of multiple step rotations as shown in Figure 4. The first game (the upper-left image) was simply an opportunity to practice rotation of various objects. The app showed a 3-dimensional object next to the 3 axes. Students could then rotate the object as they chose by touching on the rotation icons (shown at the right side).

The second game (the upper-right image) required students to rotate the object so as to match a second (and smaller) copy of the object appearing to the right (behind the axes). This game had multiple levels, the first of which only required rotation around the Z axis. It also showed the letters "SR" (in yellow) rotated along with the object. Students were asked to rotate the object so that it matched the goal object, and so that the letters right right-side-up at the bottom of the paper. Later levels of this game included just the Y axis, just the X axis, then any axis, and then any axes in 2 steps of rotation.

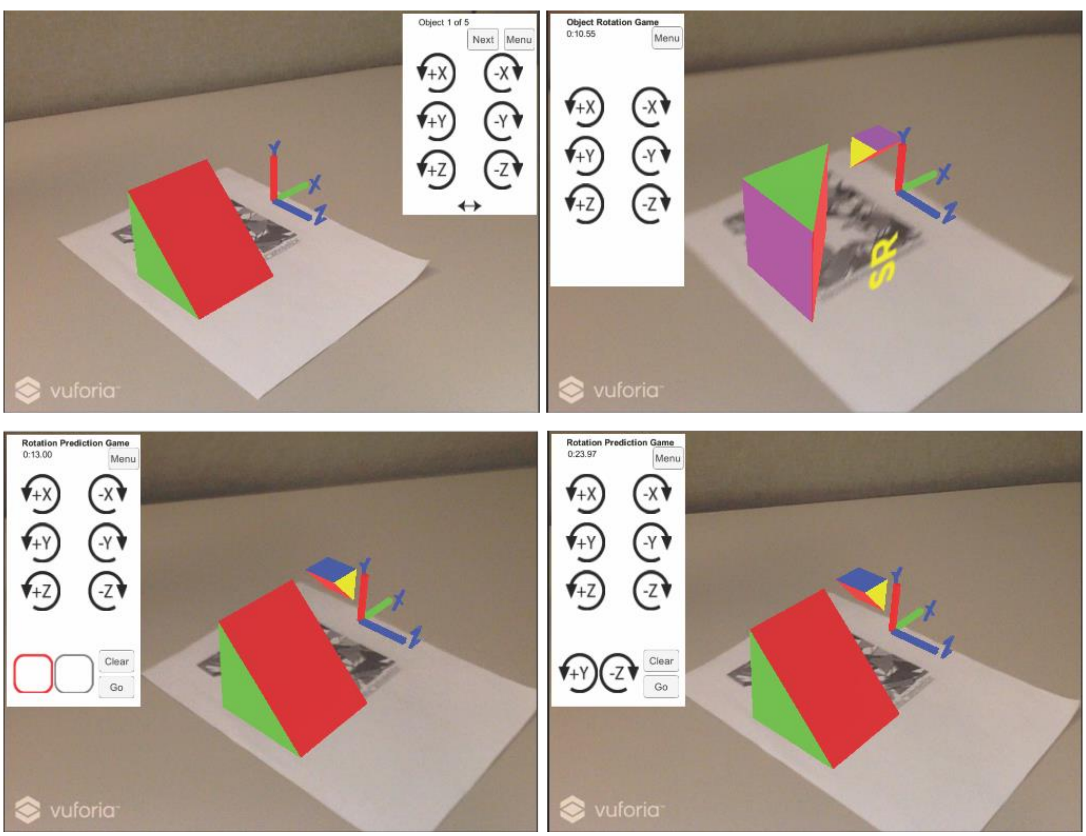

Figure 4: Handheld augmented reality

The third game (in the lower row) required students to predict what rotation steps would be needed to make their object match the orientation of the model object. That is, they had to choose 2 rotation moves before either move was performed. The lower-left image shows two empty squares in the lower-left corner, one red and one blue. When students touched a rotation icon, it would appear in the box. Once they had chosen the 2 rotation steps, they would touch "Go" and the rotations would be performed. If they were correct, the app would move on to the next object. If they were wrong, those rotations would be visibly rolled back, and students would try again.

In all of these games, students were time and their scores were ranked so they could compete with each other.

Research Questions

Our research questions were as follows: First, do students using the handheld augmented reality app for in-class and out-of-class practice show greater pre-post course improvements on a mental rotation assessment than a control group working with traditional paper/pencil/textbook exercises only? Second, do students using the app report higher increases in terms of enjoyment of and perceived competence in mental rotation tasks? Third, given the exploratory nature of this research and the early stage status of the AR app, we were further interested in the students' experience of the app, its ability to generate realistic 3-dimensional object perceptions (in other words, the extent to which users report perceiving objects shown as almost tangible). We were interested in the AR app's enjoyability overall and in terms of different interaction modes/games, its perceived potential to motivate practice and build mental rotation skills, and the perceived advantages or disadvantages of the app as compared with the traditions pencil/paper and textbook approaches. To gain insight into these subjective experiences with both some breadth and depth, we combined quantitative and qualitative approaches.

Context and Method

At Michigan State University, new students who indicate an interest in engineering take the PSVT:R assessment of mental rotation. Those who score below a threshold (passing score) were encouraged to take a 1-credit course designed to help them develop their spatial reasoning ability. Roughly half of these students actually take this 1-credit class (Walton, Urban-Lurain, Idema, Hinds, & Briedis, 2015). This class had 4 sections, two of which served as the control group and two of which served as the experimental group.

The control group followed very closely the strategy described by Sorby et al. (2013). For example, students used grid paper to draw orthogonal projections of object portrayed using an isometric projection. The experimental group had the same curriculum and tests as the control group with the addition of periodic use of the augmented reality app. During 4 class sessions, 10-15 minutes was set aside to allow students to use the app. In an effort to motivate students to use the app, high scores were recorded and reported to the students as well as on a website. Furthermore, a $5 gift card was given to high scorers in each section during tournament rounds.

Of the 94 students, 47 were in each of the experimental and the control groups. Of the 78 who reported their gender, 27 were women (24%) and 51 were men (45%). We used a range of quantitative and qualitative data. The PSVT:R pre-course scores and the PSVT:R-based final exam served as measures of achievement in mental rotation. A survey administered at the beginning of the course included participant demographics as well as enjoyment of and perceived competence at spatial reasoning activities based on Ryan's (1982) longstanding Intrinsic Motivation Inventory (IMI). A post-course survey again assessed enjoyment and perceived competence with regards to spatial rotation.

For members of the experimental group, in-app data collection/trace data of the overall time spent on the app was recorded. Participants in the experimental group were also asked to assess their enjoyment and perceived competence regarding use of the AR app itself, and to compare the app to the textbook in terms of its perceived helpfulness in developing mental rotation skills, enjoyability, and potential to motivate practice of mental rotation problems. Participants were also asked to rate their experience with different components of the app, the perceived realism of the objects displayed, and to make suggestions for improvements of the app and its implementation within courses.

After the course and the final surveys were completed, we completed interviews along similar dimensions with two members of the experimental group and two members of the control group. The control group members were given a brief introduction to the app in the interview in order to assess initial user reactions.

Results

App usage and performance data

The most important limitation of this study is how little time students actually used the app. The maximum time that students used the app was 46 minutes with a mean of 19 and a standard deviation of 11. In terms of academic achievement, a t-test revealed no significant difference between the experimental group's and the control group's improvement on the PSVT:R or the two group's changes in enjoyment and perceived competence regarding mental rotation tasks. Figure 5 shows the pre/post scores on mental rotation. Students falling above the 45 degree line (i.e., almost all) had improved post-test scores, regardless of their experimental versus control group membership, replicating Walton et al., 2015. A single control group participant had a lower post-test score. Not finding significant group differences is no surprise given that merely 2% of class time actually involved students using the app.

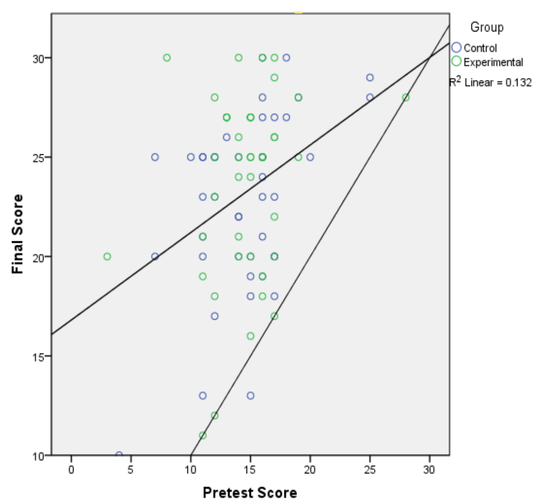

Figure 5: Pre-test vs. post-test scores

Perceived Realism of app's 3-D objects

We used two survey items to assess students' perceptions of how realistically the app was rendering three-dimensional objects: "When using the app, I felt like I could almost reach out to touch the objects" and "When using the AR app, I felt like I could almost turn the objects in space." Responses to these items were highly correlated and were averaged into a perceived realism index (Cronbach's alpha=.96). With a range of 1 (strongly disagree) to 7 (strongly agree), average perceived realism was 5.02 with a standard deviation of 1.95. Figure 6 shows the frequency of these responses. Scores of 5 or higher indicate some to strong agreement with relevant indicators.

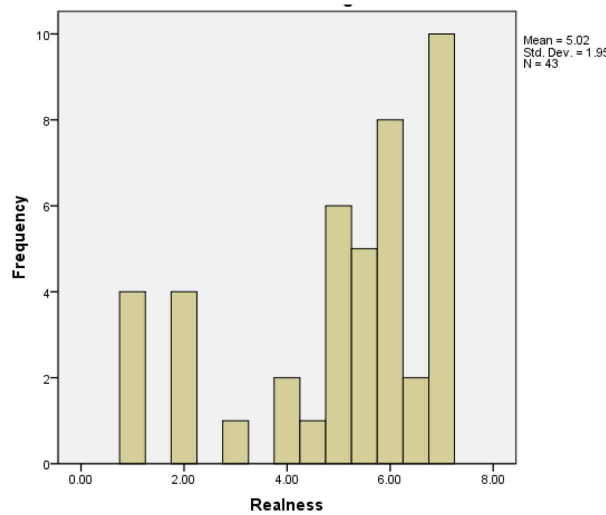

Figure 6: Perceived realism of the AR app's rendered 3-D objects

Enjoyability

As shown in Figure 7, survey data revealed that on a scale from 1 (strongly disagree) to 7 (strongly agree), experimental group participants tended to agree either somewhat or strongly to items such as "I enjoyed using the app in general" (M=5, SD=1.4); "I enjoyed using the prediction game" (M=5.07; SD=1.33); "I enjoyed using the rotation game" (M=5; SD=1.48); and "Compared to the textbook, the app was more enjoyable" (M=3.81, SD=1.11, on a scale from 1-5 where 1 represents a strong textbook preference and 5 a strong app preference).

In our interviews, two students from the experimental group reported that working with the augmented reality application was more enjoyable than working with traditional pencil and paper activities for two main reasons. First, they had no prior experience of using augmented reality apps for spatial reasoning, and it was interesting for them to be able to interact with the app. Second, the competition features and rewards added more gaming elements to the app. For instance, one student said:

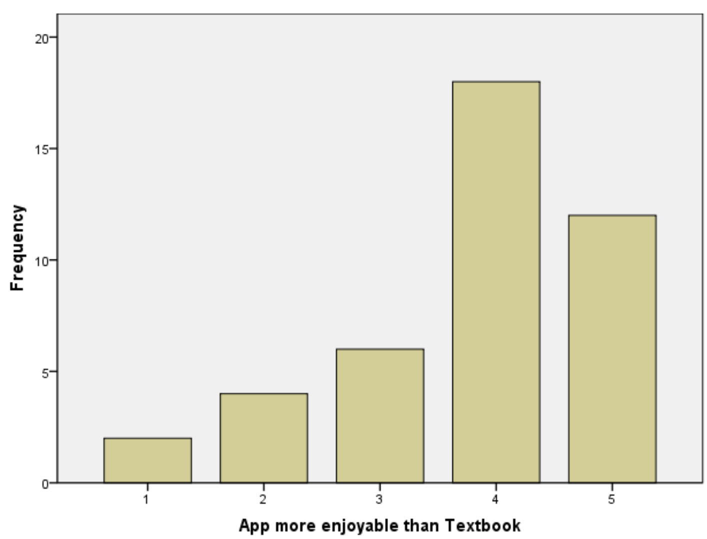

Figure 7: Comparing enjoyability of app versus textbook

It [the app] was a lot more fun because it was just, it was kind of like a hologram, I guess, and that's

> not something that I’m used to playing with. So that was pretty fun. And then the game was pretty competitive, when we were trying to see who could get the fastest score in the class. I had the fastest score of all for ten minutes so it’s kinda competitive and that’s always fun.

The other student also mentioned:

> I thought it [the app] was cool how you use your camera and you shine it on that paper and then a 3-D object shows up. I’ve never seen anything like that before. And then I thought the games were fun. They made improvements to the app so there were like more games or like more levels or whatever and I thought that was cool, too.

Perceived helpfulness

Survey data revealed that app users on average perceived the app as slightly to moderately more helpful than the textbook for developing mental rotation skills (M=3.63, SD=1.20, with 1=strong textbook preference and 5=strong app preference), but the responses were more varied here (Figure 8).

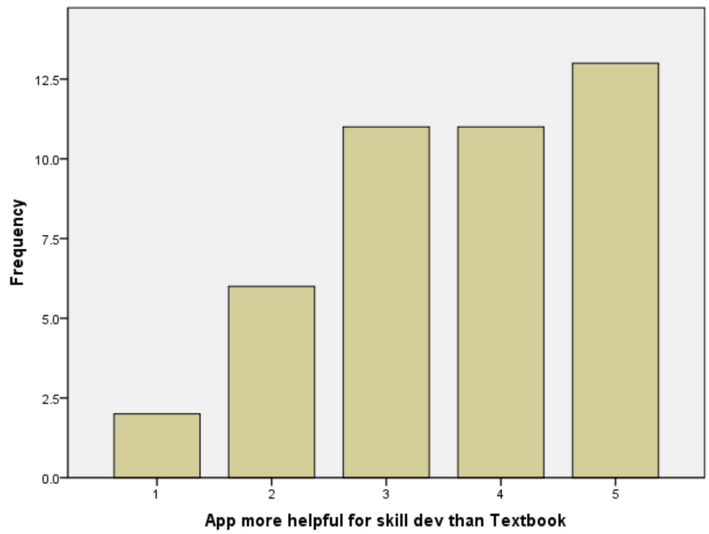

Figure 8: Perceived helpfulness of app versus textbook

The two students from the experimental group mentioned that the app enabled them to look at an object from all different sides and “actually see” how it rotates around each axis. One student explained:

> On pen and paper, it was just harder to, even though I knew which axis was being rotated, it was just hard to imagine it on pen and paper. So when they would tell us to do a Y rotation, a clockwise Y rotation, it would be hard to just see that on the sheet of paper. So using the app, I could actually press the Y rotation button and I could see which way it would rotate, which way it would turn. So that kinda got into my brain, like muscle memory in a way. So I know which way it’s turning or if it was a clockwise Y rotation or how it would look if it was a Z rotation or stuff like that. Instead of just guessing on the sheet of paper, I was actually able to see it happen on the app so that helped a lot.

This student further mentioned that the app served as “a reference point” when she was working on rotation problems on a piece of paper, helping her to imagine the objects and rotations in her mind.

In addition, two students from the control group had the chance to work briefly with the app after they completed the course and surveys. They both considered the app as more helpful in two aspects. First, the game of prediction of multiple-step rotations helped them better understand why the order of rotations matters:

> We did like multiple rotations over different axes (with pencil and paper). He [the instructor] told us that when you, like the order matters and to me, I was like, I don’t see how it does but when I did it

> on like the app, I actually saw like it does matter because it shows you how you flip it and tells you if you're wrong.

Second, the app provided feedback in a timelier fashion. For instance, one student said:

> [The app provided] More immediate feedback. So like if you're doing the homework, like you don't know if like you did them right until like a week later, after he [the instructor] gives it back...So it doesn't really like help if you just have to do it [the paper and pencil quiz] and turn it in. Whereas this [the app], you can like see right away if you did it right. So you know if you need to like study it more.

To our surprise, one student from the experimental group expressed that the app was even helpful in developing other kinds of spatial abilities such as imagining cross-sections although the app was primarily designed for developing mental rotation ability:

> When it comes to cross sections, it was easier to see when I could actually rotate on the app, instead of just seeing a whole figure and, well, seeing the whole figure itself and being able to move it made it easier to imagine a cross section instead of just being on a sheet of paper. So like I said, I had applied what the app gave me, like the skills I developed from the app, I use it for calculus II. Like we're dealing with revolution of solids and you have to look at cross sections. And now that I can see the object that I'm..., the object we have to draw on the sheet of paper, I can see now where the cross sections, how they will be circles or squares and the app helped me be able to do that on my own.

Students suggested that it would have been more helpful if the objects in the app were more aligned with those they had in their assignments.

These findings were in line with themes based on answers to the open-ended survey question, "the AR app would have helped me develop spatial reasoning ability more if...". Of 21 responses, 5 described closer alignment with course tasks. Increased variety of games and problems were mentioned four and three times respectively as factors that would increase spatial reasoning development. Five students mentioned a desire for scaffolding (e.g. "if it gave you hints after you got answers wrong"). Three stated that structured use in class or other incentivisation would have improved the app's ability to support spatial reasoning development.

Motivation

Similar to perceived helpfulness, our survey data revealed that app users on average perceived the app as slightly to moderately better at motivating spatial rotation practice than the textbook (M=3.63, SD=1.20, with 1=strong textbook preference and 5=strong app preference), but as with perceived helpfulness, the responses were somewhat varied (Figure 9):

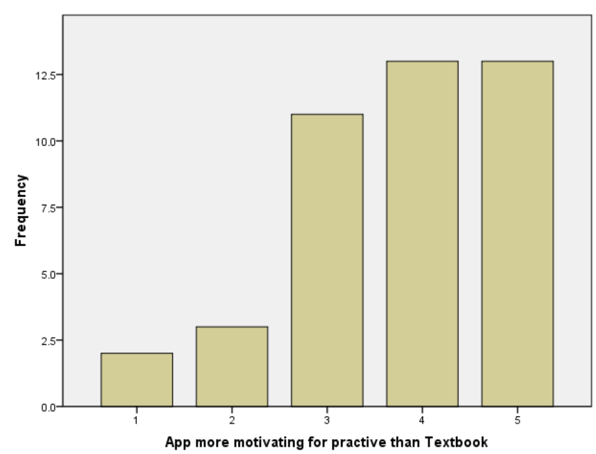

Figure 9: Motivation of app versus textbook

Interview data provided insight into how and why students' perceptions of the app varied in terms motivating spatial rotation practice. One student from the experimental group and the two students from the control group reported that working with the application was more motivating than working with traditional pencil and paper activities because (a) the app was more enjoyable to play with, (b) the app provided immediate feedback, and (c) the competitive features made the app more engaging. The other student from the experimental group expressed, however, that the app was less motivating because the pencil and paper activities were required in the course, whereas the use of the app was optional.

These findings also paralleled themes based on answers to the open-ended survey question, "I would have played the AR app more if ...". Of 26 responses, eight stated that they would have used the AR app more if it offered a larger variety games and options. Two students explicitly stated closer alignment with course tasks and homework problems as a possible motivator, besides technical concerns such as bugs and battery drain, as well as interface shortcomings.

Discussion

The biggest limitation of this study was the limited amount of time students spent using the app. Given that time spent with the app accounted for merely 2% of in-class time, it is no surprise that no significant impact was found on class outcomes. Another important limitation is that the app was under continued development during the course of this study. As such, the lack of statistically significant effects on course outcomes is not surprising. On the other hand, the indications of perceived realism, perceived helpfulness, enjoyability, and motivation all suggest that further study is warranted regarding potential benefits for development ability and confidence in mental rotation. Using the design thinking orientation to educational interventions (Yeager et al., 2016), a new study is underway using the next iteration of the app and the associated educational strategies.

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Images:

Figure 1: https://www.youtube.com/watch?v=TT-VYMFJmoE