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Improving Spatial Perspective Taking Ability of Middle School Students Using Augmented Reality

Anveshna SRIVASTAVA* & Chandan DASGUPTA
Educational Technology, Indian Institute of Technology Bombay, India
*anveshna.sriv@gmail.com

Abstract: There is great interest in understanding the pedagogical value of Augmented Reality (AR) based systems. Here, we measured the effect of an AR tool - GeoSolvAR - on spatial perspective-taking ability of students. The GeoSolvAR application helps learners to visualize 2D images as 3-D objects. In this pilot study, we report data from 16 middle school students who were individually administered the online Perspective Taking Spatial Orientation Test (PTSOT) both prior to and after performing the GeoSolvAR activities. Our results suggest that the students showed a significant decrease in angular errors on PTSOT in the post-test with a large effect size (Cohen's $d = 1.26$). A cohort-level analysis also revealed larger and equal effect sizes in perspective-taking spatial abilities for both males and females (Cohen's d = 0.69). However, our finding with a subset of 10 students reveal that the GeoSolvAR activities were challenging for the students and that there was a positive but non-significant correlation of students' GeoSolvAR activity with their PTSOT performance. We discuss the limitations, and the way forward for this work, while making a case for using the GeoSolvAR application as a spatial-skill training tool.

Keywords: Spatial Skill, Perspective-taking Ability, Augmented Reality, 3-D Visualization, Middle School Students

1. Learning and Spatial Reasoning

Spatial reasoning is concerned with how we factor the objects in the world, their shapes, their locations, their relations to each other, their potential movement paths, in our decision-making processes (Newcombe, 2017). This reasoning is visible in seemingly inconsequential actions like navigating the spaces in our homes to potentially consequential actions of manipulating the spatial structure of a biomolecule. In the context of learning and social success, spatial reasoning abilities have been particularly demonstrated to play a significant role in performance in school (Lowrie & Diezmann, 2007) and career achievement in STEM (science, technology, engineering and mathematics) and related fields (Wai, Lubinski, & Benbow, 2009).

Given considerable evidence on the long-term impact of spatial reasoning ability on learning and achievement in STEM subjects, recognition of and emphasis on spatial abilities as an essential component of learning foundations, on par with the three *R's* of reading, writing and arithmetic is warranted (Ishikawa & Newcombe, 2021). Just as learners can be trained on and their skills honed for competency in the three R's, they can also be trained to improve their spatial abilities. This follows from multiple streams of research which suggest that spatial skills are sufficiently malleable to permit effective and economically feasible training (Francis, Rothschuh, Poscente, & Davis, 2021).

Literature on spatial ability suggests differentiation of two kinds of spatial transformations- a) object-based transformation, where an object is imagined to transform and, b) perspective-based transformation, where one's point of view is transformed in relation to something else (Bryant & Tversky, 1999). In this study, we focus on the latter form of spatial ability which is concerned with mentally representing and perceiving a situation from a different viewpoint than one's own (Galinsky, Ku & Wang, 2005).

Spatial perspective-taking is a two-step process. In the first step, one mentally simulates the action of situating one's body at a different location from where it actually is and this facilitates the second step of imagining the perspective one would have by being located in the new space. Thus, spatial perspective-taking is effort intensive (Tversky and Hard, 2009). Further, since different perspectives might help one uncover specific nuances of a problem, it is argued that perspective-taking promotes learning by filling in gaps in comprehension and enabling mental manipulation of the frame of reference.

2. Perspective Taking Spatial Orientation Test

The Perspective Taking Spatial Orientation Test was first developed by Kozhevnikov and Hegarty (2001). It is a measure of the ability to make egocentric spatial transformations in which one's egocentric frame changes with respect to the environment (Thurstone, 1950). For the present study, we used the online version of the PTSOT (Friedman, Kohler, Gunalp, Boone & Hegarty, 2019). This test assesses participant's ability to imagine how a stimulus array will appear from another perspective. Participants were shown an array of seven 2-D objects (see Figure 1)..

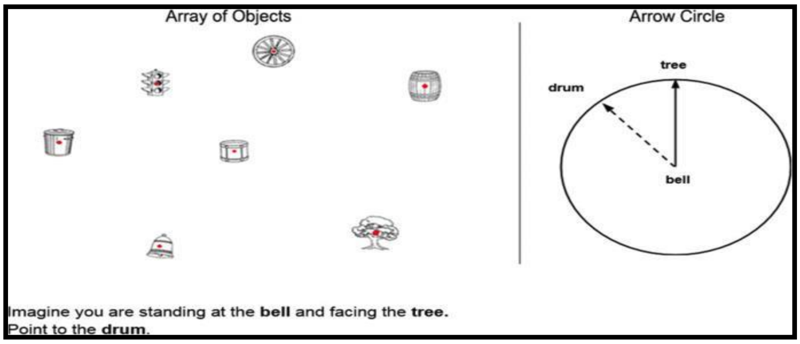

Figure 1. A sample question from the online PTSOT test.

Figure 1 represents a screenshot of a PTSOT question where an array of 2-D objects is shown on the left and on the right, an 'Arrow Circle' is represented. At the left bottom, one can see the question which asks the participant to imagine being positioned at a specific object ('bell' in the example), relative to a second object (the orienting cue; 'tree' in the example) and, the participant is further asked to predict the direction of the third object (target object; 'drum' in the example). In the arrow circle, the participant was always placed at the center, while the orienting cue was placed right in front of the imagined position (center). The task was to move the shown arrow, using mouse, in the circle so as to represent the direction of the 'target' object. The PTSOT had 12 questions which the participants had to complete within a time span of 5 minutes. These questions appeared in a randomized manner and responses were scored for angular error averaged across trials for each participant. We used PTSOT both as a pre-test and as a post-test for all the participants.

3. 3-D visualization and the AR tool- GeoSolvAR

The ability to mentally translate and visualize 2-D images into 3-D forms is a critical spatial ability, used in the learning of sciences (Srivastava & Ramadas, 2013), technology (Norman, 1994), engineering (Sorby, Drummer, Hungwe, Parolini, & Molzan, 2006) etc. It has been noted that students generally face difficulty with 2-D to 3-D transformations (Akasah, & Alias, 2010). Further, it has been shown that robust gender differences, favoring males, exist in perspective-taking spatial orientation abilities (Friedman, Kohler, Gunalp, Boone, & Hegarty, 2019).

Motivated by the last two arguments, and with support from literature on training for improving spatial skills, we studied an Augmented Reality (AR) tool- '*GeoSolvAR*' -which targets middle school students and helps them to solve problems related to visualization of 3-D geometric solids (Kaur, Pathan, Khwaja, & Murthy, 2018). The GeoSolvAR application is freely accessible on the web interface and can be installed on Android tablets/ phones with minimum Android OS version 4.0. This application introduces basic concepts of 3-D views pertaining to directionality of objects, namely- top view, front view and side view. It has a set of six different activities related to different objects (see Figure 2).

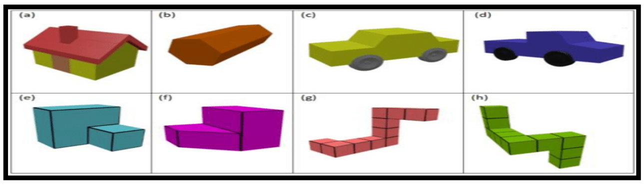

Figure 2. The 2-D images of models that were augmented via GeoSolvAR (Reproduced from Kaur, Pathan, Khwaja, Sarkar, Rathod, & Murthy, 2018)

AR tools function by superimposing computer-generated images onto an observer’s view of the real world and, thus, have the potential to help with 3-D spatial skills (Kaufmann, & Schmalstieg, 2003). We found this opportunity with the GeoSolvAR application to see if the augmented 3-D view of the 2-D objects (in Figure 2) would help students to develop a changed spatial perspective for observing the objects in the environment. Specifically, AR activities, like in Figure 3, we hypothesized, can help with students’ perspective-taking spatial orientation ability.

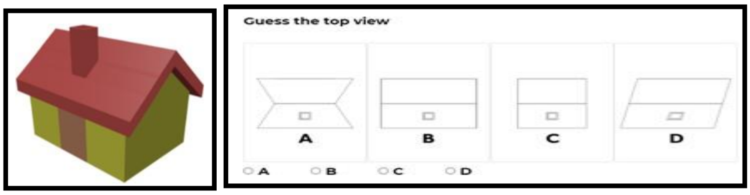

Figure 3. GeoSolvAR activity sample question. On the left, object 'house' is shown and, on the right, a question on predicting the 'top' view of the house is asked.

Further, since robust gender differences, favoring males, are known to exist on spatial abilities (Sorby, Drummer, Hungwe, Parolini, & Molzan, 2006), we began with the null hypothesis that no gender difference would exist on students' performance on the PTSOT with respect to the AR tool. To test these hypotheses, we conducted this pilot study where PTSOT was used as both pre- and a post-test and the GeoSolvAR 3-D visualization activities were used as an intervention.

4. Methods

4.1. Sample

16 middle school students (M=9; F=7; Average Age = 14.1 years; SD = 1.1) voluntarily responded to a general call for the pilot study. Their parents’ consent and their assent were received before the conduct of the study. This study was approved by the IRB of the institute and the participants were free to leave the study at any point of time with no incurrent cost to them.

4.2. Data sources

The GeoSolvAR activities were conducted online on a web interface while the screen of the computer was being recorded. This provided us with data about the responses that students generated for each activity. Further, a student’s performance on the computerized PTSOT was received at the backend of the experiment. This performance data carried information about the angular positions estimated by the individual for each target object for each trial in the set of 12 randomized questions. It also reported the angular error or the degree of deviation of the estimated angle from the actual orientation angle of the target object for all the trials and, finally, an average angular error was also computed across all the trials for the individual.

4.3. Task protocol

The study was divided into three phases, spread over a span of minimum 2 days and maximum 10 days, subject to the time-schedule of the students. In the first phase, the PTSOT pre-test was administered to a student. In the second phase, the student was introduced to the GeoSolvAR tool and was asked to perform all the six activities. In the third phase, the PTSOT post-test was administered. The first phase occurred on the first day, while the second and the third phases were conducted one after the other on the next day of student's arrival for the study. On an average, the gap between the first and the second day of the study was 5.3 days (SD = 3.59).

This gap was designed to reduce the possibility of simple recall of the pre-test questions and consequent biasing of the post-test data. It is to be noted here that students were not informed that they would be asked to do the PTSOT again on their other day of the study and, hence, it is likely that the students did not leave any mental markers to help them in the post-test questions.

5. Results

We analyzed the data to observe- a) if there was a change in student's performance on the spatial orientation task, b) student's performance on the GeoSolvAR activities, and c) if there was a correlation between student's performance on the PTSOT and the GeoSolvAR activities. We also performed a cohort-level analysis to find if gender played a role in spatial training through the GeoSolvAR activities. We share the findings from our study below.

5.1. Significant improvement in spatial perspective-taking ability

Overall, we found that the average angular error across the participants got significantly reduced in the post-test, or, the participants showed significant improvement in their perspective taking spatial orientation ability. A paired-samples t-test revealed that participants' average angular error degree in the pre-test (M = 74.91, SD = 19.16) was reduced by around 12 degrees in the post-test (M = 62.39, SD = 21.31), t (15) = 4.89, p = 0.00019. An extremely large effect size (Cohen's d = 1.26) was observed.

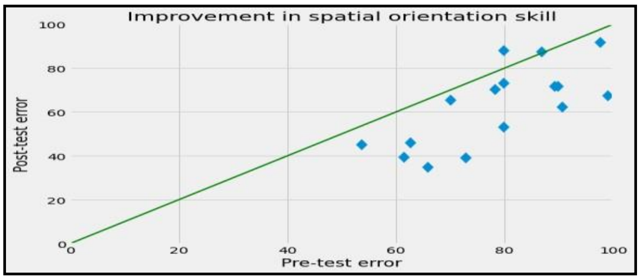

Figure 4. Scatter plot of pre and post angular errors for each participant (n=16)

Figure 4 shows a scatter plot comparing pre and post angular errors for all the 16 participants. The diagonal line depicts y=x, suggesting no change in the pre and the post scores. The students above the line show an increase in angular error and the ones below show decrease in angular error. Regardless of the small sample size, an average reduction of 16.7% in spatial orientation error is observed.

5.2. Students found GeoSolvAR activities challenging

A total of 14 predictive questions on the 3-D visualization activities were asked from the students as part of the GeoSolvAR tasks. For each correct response, students received score '1', else '0'. After solving activity questions, students were asked to use the GeoSolvAR application to view the augmented 3-D image of the 2-D objects shown in the activity question and they were free to change their responses, if they felt the need. Here, we report data from 10 students only and discard the rest where response to even one question was missing.

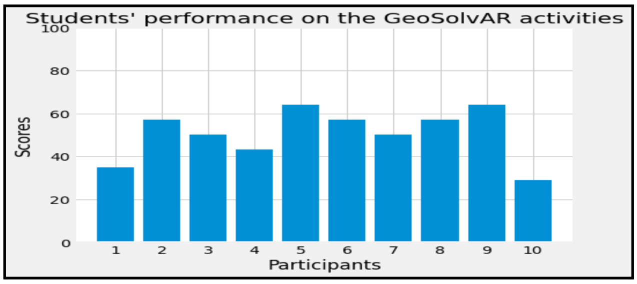

Figure 5. Students' scores on the GeoSolvAR application summed across all the 6 activities and presented on a scale of 100

Figure 5 shows a bar graph to depict students' scores on the GeoSolvAR activities on a scale of 100. The average score of the students is 50.6 (SD = 11.8), the maximum score attained was 64 and the minimum score was 28. This suggests that students found the GeoSolvAR activity challenging.

5.3. Positive correlation between PTSOT improvement and GeoSolvAR performance

We found a small positive but not significant correlation of the subset of students' perspective-taking ability with their performance on the GeoSolvAR activities, r (8) = .227, p = .53. The positive correlation discovered is encouraging for the use of the GeoSolvAR application for spatial skill training. However, given the small sample size, we cannot draw conclusions about the causal connection between the use of the application and its impact on students' perspective-taking spatial ability.

5.4. Large effect size gains in spatial orientation abilities of both males & females

Grouping the data into the two cohorts of male and female, we were able to analyze the role of gender on the perspective-taking spatial orientation ability. A paired samples t-test revealed that the average angular error in males in the pre-test (M = 78.29, SD = 11.78) was reduced in the post-test (M = 64.26, SD = 21.11), t (8) = 1.96, p = .08. The paired samples t-test in the females, similarly, revealed that the average angular error in the pre-test (M= 70.54, SD = 26.33) was reduced in the post-test (M= 59.9, SD= 23), t (6) = 1.69, p = 0.14. Notably, the effect size seen was large (Cohen's d = 0.69), and equal for both the males and the females.

5.6. Control

We understand that there's a possibility that students might be able to perform better on the post-test, just based on the repetition of the elements of the pre-test. However, this possibility is reduced because students are not provided with any feedback on their performance on the pre-test. Further, the average error scores were not shared with them after the test and, hence, students did not have any means to assess their performance. Thus, with no assessment baseline, students could not calibrate their actions in the post-test.

Nonetheless, for completeness, we administered the PTSOT task twice to two adults, one male (19-year-old) and one female (35-year-old). The individuals were not given the GeoSolvAR activity and were asked to repeat the test soon after they completed the first test. We found that the average error reduced by 0.91 degrees and 0.5 degrees in the post-test for the male and for the female respectively. This is an order of magnitude lower than the 12 degrees of average error reduction that we found in the 16 students who worked with the GeoSolvAR application.

6. Limitations & Way Forward

Our pilot study has revealed potential significance of the GeoSolvAR application as a tool to help improve the perspective-taking spatial orientation abilities of middle school students. We further found that the AR application led to large and equal effect size in both males and females (Cohen's d = 0.69).

However, given the small size of our pilot study, we cannot conclusively draw inferences about the role of the GeoSolvAR application in enhancing students' spatial ability.

Further, since students found the GeoSolvAR activities to be challenging, we might need to modify or improve the AR tool by including certain scaffolds, like reflection spots or well-placed cues, to help students navigate through the visuo-spatial activities (Kaur, Pathan, Khwaja, & Murthy, 2018). The limited data set also made it difficult to make sense of the low correlation between the GeosolvAR performance scores and the performance on the perspective-taking spatial ability.

For this work, we could not study the qualitative aspects of students' interaction with the AR tool and, hence, we are not able to pin-point specific underlying mechanisms that explains our result of high improvement on the spatial perspective-taking ability using the AR tool.

Nonetheless, our preliminary findings suggest that the GeosolvAR application has practical implications and that it can be readily used in a classroom setting. We look forward to build on this work and conduct more studies with larger groups of students. For future studies we also intend to analyze the video data for students' body movements, hand gestures and/or facial expressions to capture behavioral markers indicative of students' engagement with the mapping of the AR and the spatial tasks, like trying to orient one's body that can bring the participant closer in perspective to the imagined orientation. This would help us understand the different aspects of the AR tool which is helping students to improve their perspective taking spatial ability.

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