

AR-Classroom: Usability of AR educational technology for learning rotations using three-dimensional matrix algebra

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Abstract— The AR-Classroom application utilizes augmented reality technology (AR) to make the three-dimensional (3D) rotations underlying matrix algebra visible and interactive. The AR-Classroom has physical and virtual versions, where users can perform rotations using a physical LEGO model or by manipulating the application's x, y, and z axes sliders to rotate a virtual model. Both versions provide 3D matrices, color-coded axes lines, and a green wireframe superimposed onto a LEGO model to represent transformations. To ensure that the AR-Classroom makes learning 3D matrix algebra more engaging and accessible, two usability tests were used to evaluate the discoverability and usability of the app.

The benchmark test assessed usability in the AR-Classroom's original format, and recommendations were made to improve the app., such as adding additional instructions on model set-up, restructuring, and updating the instructions, and turning the 'visualization type' function into a button to make it easier to find. After the improvements, the updated usability test assessed usability again so that the impact of the modifications could be evaluated. Participants followed similar procedures in both the benchmark (N=12) and updated usability (N=12) tests. Participants completed a pre-test assessing their math abilities and confidence, watched a video on geometric transformations, and then were randomly assigned to interact with either the physical or virtual version of the app. While interacting with the app, participants were given tasks to complete while thinking out loud and provided an ease-of-use rating from 1=very easy to 7=very difficult (i.e., SEQ score). Once done interacting with the app,

participants completed a post-test assessing their math abilities and confidence and provided feedback on their overall experience with the app (i.e., SUS).

A thematic analysis was conducted after each test to identify and code themes in interaction and compare findings from the benchmark and updated tests. Results indicated that after changes were made to the app, the usability of both versions significantly improved: users were better able to set up the space shuttle model, effectively utilize the in-app instructions, and quickly access all of the app's features. Findings from the updated usability test contribute to enhancing the AR-Classroom app and further its use in higher education classrooms for learning matrix algebra.

Keywords— Augmented Reality, Spatial Transformation, Mathematical Representation, Rotation Matrix, Embodied Learning

I. INTRODUCTION

Spatial skills allow individuals to create imaginary spatial images and manipulate them to solve various practical and theoretical problems [1], [2]. Strong spatial skills are associated with increased mathematical conceptualization [3], [4], problem-solving skills [5], creative and higher-order thinking skills [6], [7], and design and visual representation skills in engineering [8], [9], [10]. Visualizing two- or three-dimensional objects in one's mind (i.e., spatial visualization) and rotating those images (i.e., mental rotations) are critical spatial skills for

those within science, technology, engineering, and mathematics (STEM) [11]. Moreover, there is evidence for the predictive validity of spatial skills to make inferences about academic success within STEM areas [12], [13]. Thus, developing students' spatial skills and understanding of theoretical mathematics is essential for pursuing careers in aerospace engineering, mechanical engineering, civil engineering, computer graphics, and other STEM fields. However, despite the importance of performing mental rotations for these fields of study, building students' spatial and mathematical skills has challenged educators.

Developing spatial visualization and mental rotation skills can be environmental or experiential, suggesting that multi-sensory applications may enhance these skill sets [14]. Providing students with physical and virtual models to simultaneously touch, see, and manipulate can aid information acquisition. Augmented reality (AR) can facilitate these dual sensory experiences that permit deeper understanding by superimposing virtual objects or concepts onto the real world [15]. AR supports understanding complex phenomena, such as matrix algebra, by providing unique visual and interactive experiences that combine real and virtual information to help communicate abstract problems to learners. Allowing the learner to directly and immediately interact with mathematical representations can strengthen students' spatial skills and aid cognitive offloading. Augmenting abstract mathematical concepts such as geometric transformations and their matrices allows students to manipulate virtual and physical objects. For example, the dynamic processes of augmenting mathematical concepts and direct tangible interactions provide an intuitive way for students to interact with three-dimensional (3D) matrix algebra. Studying spatial transformations and linear algebra allows students to learn important mathematical concepts, develop higher-level reasoning skills, and utilize different mathematical representations. However, students often struggle with generalizing geometric reasoning, understanding symbolic notation in linear algebra [16], and transitioning to matrix representations [17].

AR enhances users' perception of the natural world by overlaying digital images through AR glasses or mobile devices. Previous research on AR-assisted geometry learning, including GeoGebra AR, has focused on projecting virtual 3D models onto physical surfaces like desktops or book pages without integrating virtual and physical models [18], [19], [20], [21]. Building on the current body of literature on AR and 3D modeling for learning, our AR-Classroom research explores how AR can support the comprehension of spatial transformations utilizing integrated and interactive virtual and physical models.

Two usability studies examined user interactions within an AR application for learning 3D matrix algebra called AR-Classroom. AR-Classroom consists of a tutorial for AR model registration and two workshops – virtual model rotation (Workshop 1) and physical model rotation (Workshop 2). Data collection included qualitative data through observations and user-reported experiences while interacting with the app and quantitative data via usability measures and a mathematics test. The overarching goal of these studies was to examine users' experience with an initial version of the app via a benchmark

usability test, make recommendations for app improvements, and then examine the impact of changes made on app usability via an updated usability test. These usability studies aim to answer the following research questions: 1) What do users discover about the AR-Classroom's tutorial and two workshops? 2) What features of the AR-Classroom are easy versus challenging to use? 3) How do changes made to the AR-Classroom enhance the application's usability for learning 3D matrix algebra?

A. AR-Classroom

The present study assesses the usability of AR-Classroom, an educational application for learning 3D geometric rotations and their mathematical representation through either a virtual or physical interactive environment. The app aims to make the rotations underlying matrix algebra visible and interactive for the user by superimposing mathematical information onto real-world objects. Furthermore, AR-Classroom utilizes AR technology and a space shuttle LEGO model to assist students in understanding the math concepts behind geometric rotations by visualizing the entries within transformation matrices. The app includes a model registration tutorial and virtual and physical workshops. The details of the technology development are described in "AR-Classroom: Augmented Reality Technology for Learning 3D Spatial Transformations and Their Matrix Representation" [22].

B. Tutorial: Model Registration

To guide users in registering the space shuttle LEGO model (i.e., using the app to identify the LEGO model and superimpose virtual objects onto the image from the webcam of the computer, which operates as an AR-enabled device), users first start the app and select the 'Tutorial: Model Registration' button on the home screen. Once in the tutorial, on-screen instructions on how to get the correct AR registration and a white outline of the model on the screen. The user then registers the model by holding the LEGO space shuttle in the camera's view to match the white outline image on the screen until the superimposed virtual model (i.e., green wireframe) appears (Fig 1 and 2). Once the LEGO model is registered, the user will click 'complete' on the bottom of the screen and be redirected to the home screen, where they can start either the virtual or physical object rotation workshop.



Fig 1. AR-Classroom: Starting condition tutorial model registration. Note that the webcam's view and the user's view are reversed.

C. Virtual Version (Workshop 1)

The virtual workshop of the AR-Classroom displays the connection between real-world physical motion and their corresponding abstract mathematics via the rotation of a virtual model and the transformation matrix. The AR displays a superimposed virtual space shuttle model (i.e., green wireframe space shuttle and color-coded axis) on the physical LEGO space shuttle model using a connected camera. In addition, the AR displays several buttons that direct the user to the app's functions: 1) an 'i' information button to redirect the user back to the instructions that describe how to use each of the app's functions, 2) the X-, Y-, and Z-axes drop-down button that provides access to a specified axis, their associated matrices, and the axes' rotation sliders (Fig 2), 3) clicking the 'Next' button allows for switching among axes, and 4) a home button to return to the home screen. In addition, users can change the visualization type (i.e., change between the modes on the screen to turn on/off the coordinate systems or turn on/off the virtual space shuttle model) by pressing the 'V' key on their keyboard. Users can experiment with the motions of the virtual model by manipulating the axes' rotation sliders to rotate the superimposed virtual model (i.e., green wireframe).

To use the virtual workshop, users first start the app and select the 'Workshop 1: Virtual Object Rotation' button on the home screen, read the on-screen instructions for accessing and using the app's functions, and register the LEGO model. Once the physical space shuttle model is registered, the user can interact with the app by using the axes drop-down button to select the desired axis that will bring up its associated transformation matrix and then move the rotation slider to rotate the virtual superimposed space shuttle model around the selected X-, Y-, or Z-axis and see how the matrices update with the rotation.

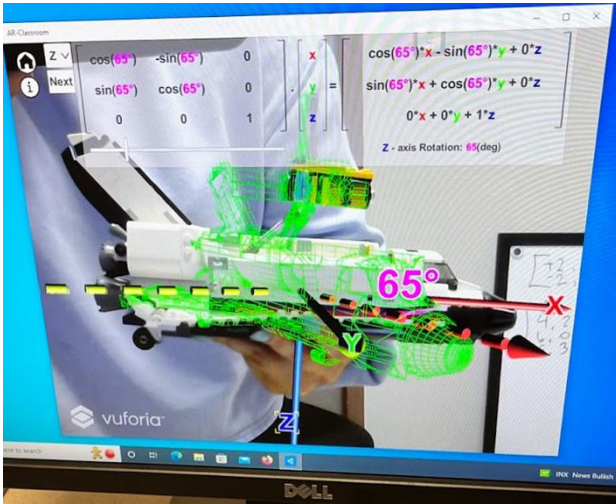


Fig 2. AR-Classroom: Starting condition, Workshop 1 (virtual object rotation): Z-axis rotation.

D. Physical Version (Workshop 2)

Like the virtual workshop, the physical workshop displays a superimposed virtual space shuttle model (i.e., green wireframe

and color-coded axis) on a physical LEGO space shuttle. The AR in the physical workshop displays similar functions to the virtual workshop; however, the X-, Y-, and Z-axes rotation sliders are unique to the virtual workshop. In the physical workshop of the app, users can experiment with the motions of the physical LEGO model by hand, affecting the parameters in the matrices by rotating the space shuttle model along a designated axis.

To use the physical workshop of the app, users follow the same steps as noted above by selecting the 'Workshop 2: Physical Object Rotation' button on the home screen and reading the on-screen instructions for accessing and using the app's functions. Once the physical LEGO space shuttle is registered, the user can interact with the app by clicking the axes drop-down button to select the desired axis. Once an axis is selected, the associated transformation matrix will be presented on screen; users can physically rotate the LEGO space shuttle around the selected X-, Y-, or Z-axis while the rotation matrix updates with each manipulation (Fig 3). While interacting with the physical model, users can access the same functions listed in the virtual workshop (i.e., color-coded axes, degree of rotation, next button, and changing the visualization mode) except for the axes sliders.

II. BENCHMARK USABILITY TEST

The benchmark usability test was conducted to gain insight into the AR-Classroom's discoverability and usability under its initial version. Potential participants were recruited via a research sign-up system in the Department of Psychological and Brain Sciences at Texas A&M University. The experiment took 1 hour, and participants received research credit for participation. The participants were twelve undergraduate students at the university. In the virtual condition (N=6), participants were 19-year-old freshmen women, with the majority having experience with 2x2 matrices and varied experience with 3x3 matrices. In the physical condition (N=6), participants were approximately 19 years old, primarily freshmen men, all having experience with 2x2 matrices and the majority with experience with 3x3 matrices.

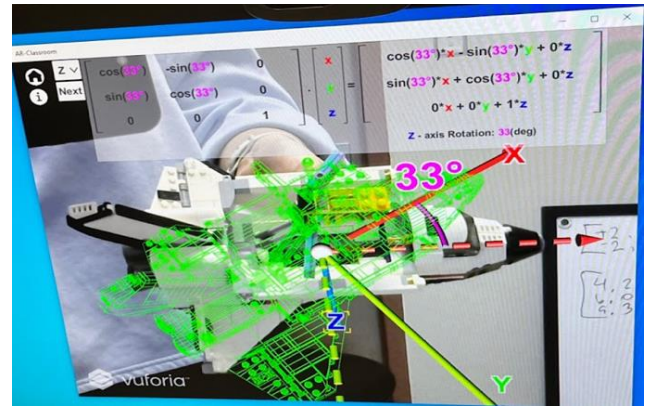


Fig 3. AR-Classroom: Starting condition, Workshop 2 (physical object rotation): Z-axis rotation.

A. Methods

The two experimental conditions, one for each workshop, followed similar procedures. Participants completed a pre-test that consisted of questions regarding demographic information

and previous experience with matrix algebra, and to gauge mathematical abilities, a sixteen-question multiple-choice 3x3 matrix algebra test (Fig 4) was developed by the research team, including a professor of mathematics. After each math question, there was a confidence rating (where 1 represented being "not at all confident" and 5 represented being "very confident" in their answer). After completing the pre-test, participants watched a brief introductory video on matrix algebra. After watching the video, the AR-Classroom application was run on the desktop computer with a webcam, and participants were given the LEGO space shuttle model. While interacting with one of the workshops, participants were asked to complete tasks related to the app's functionality. Tasks include X-, Y-, and Z-axis rotations using either the virtual or physical model, reporting the degree of rotation, changing the visualization mode of the superimposed space shuttle model, changing the Z-axis direction (pointing up or down as different conventions for different fields such as robotics or aerospace engineering), and accessing app functions. As participants interacted with the app to complete each task, they were instructed to think aloud, explaining what they were trying to do, if the task was easy or challenging, why they found it easy or challenging, and any general thoughts related to their experience with the app.

After each task, participants were asked to rate how easy or difficult it was to complete it on a 7-point scale using the Single Ease Question rating scale (SEQ). Higher SEQ scores indicate that a task was easy to complete, with lower scores indicating the inverse. When a participant provided a rating of less than 5, they were asked to describe why they found the task difficult. After interacting with the app, participants completed a post-test with the same 3x3 matrix algebra test with confidence ratings and the System Usability Scale (SUS) to assess the overall usability.

Find the matrix of the rotation which transforms quadrilateral A into quadrilateral B?

i.e. find the matrix M satisfying $\begin{pmatrix} x' \\ y' \end{pmatrix} = M \begin{pmatrix} x \\ y \end{pmatrix}$

where (x,y) are coordinates for points in A and (x',y') are coordinates for the corresponding points in B. Note: $\sin 60^\circ = 0.86603$ and $\cos 60^\circ = 0.5$

☐ a) $M = \begin{pmatrix} \sin 60^\circ & -\cos 60^\circ \\ \cos 60^\circ & \sin 60^\circ \end{pmatrix}$
☐ i) $M = \begin{pmatrix} -\sin 60^\circ & \cos 60^\circ \\ \cos 60^\circ & \sin 60^\circ \end{pmatrix}$

☐ b) $M = \begin{pmatrix} \cos 60^\circ & -\sin 60^\circ \\ \sin 60^\circ & \cos 60^\circ \end{pmatrix}$
☐ f) $M = \begin{pmatrix} -\cos 60^\circ & \sin 60^\circ \\ \sin 60^\circ & \cos 60^\circ \end{pmatrix}$

☐ c) $M = \begin{pmatrix} \sin 60^\circ & \cos 60^\circ \\ -\cos 60^\circ & \sin 60^\circ \end{pmatrix}$
☐ g) $M = \begin{pmatrix} \sin 60^\circ & \cos 60^\circ \\ \cos 60^\circ & -\sin 60^\circ \end{pmatrix}$

☐ d) $M = \begin{pmatrix} \cos 60^\circ & \sin 60^\circ \\ -\sin 60^\circ & \cos 60^\circ \end{pmatrix}$
☐ h) $M = \begin{pmatrix} \cos 60^\circ & \sin 60^\circ \\ \sin 60^\circ & -\cos 60^\circ \end{pmatrix}$

How confident were you in answering the question above?

☐ Not at all confident (I guessed)
 ☐ Low confidence
 ☐ Moderate confidence
 ☐ High confidence
 ☐ Completely confident (I know I answered correctly)

Fig 4. Matrix algebra test example questions.

B. Results

A thematic analysis was conducted to identify recurring themes in users' experiences interacting with the virtual and

physical workshops of the AR Classroom. Thematic Analysis (TA) is a systematic method for identifying, coding, and analyzing patterns of meaning in a dataset [23]. The methodology illustrates which themes or patterns are essential in describing the phenomenon under study (i.e., user-app interactions). Thematic analysis results for the present usability studies highlight the most salient reactions, thoughts, and embodiment of users' reports and what the research team observed while the participant interacted with the AR-Classroom. In addition, participants reported SEQ and SUS scores, as well as changes in math score accuracy, were examined. Though statistical significance cannot be inferred from the sample size ($N < 30$), quantitative data were subjectively reviewed for patterns and differences between the AR-Classroom versions (i.e., benchmark to updated).

1) *Tutorial*. In the tutorial: model registration, the thematic analysis results indicated that users were reading the provided text instructions. However, the most prevalent theme documented was a need for additional instructions on how the model needs to be set up. Participants would only open the LEGO space shuttle model to match the on-screen model (i.e., white outline) if explicitly told to do so or would not set up the model correctly. When the space shuttle is not fully open or does not match the white outline on the screen, this often results in loss of registration, leading to user frustration. Most participants rated registering the LEGO space shuttle model with the app relatively low (i.e., SEQ score), often citing difficulties of the reversed image view (caused by the webcam viewing angle) and AR tracking issues as adding to their frustrations. Multiple participants reported model alignment with the white outline to be challenging due to the reversed image view on the computer.

2) *Virtual (Workshop 1)*. In the virtual workshop of the AR-Classroom, participants were able to perform the majority of tasks; however, several user-app difficulties occurred. Participants would move the model around, but the model would intermittently lose the AR tracking, often causing participants to become frustrated. This theme was most apparent when participants reported that rotating the model along the Z-axis was particularly problematic as they expressed issues keeping the model registered throughout the process. Participants also seemed unsure of the objective for holding the LEGO model since, in the virtual workshop, the physical model is stagnant. When first using the app, participants would move the physical model in an attempt to perform a rotation instead of utilizing the on-screen slider for changing the rotation angles. However, after 5 minutes of free play (i.e., discoverability), most participants realized this error and self-corrected. After the initial discoverability period, most participants rated rotating the virtual superimposed space shuttle model about the X-, Y-, and Z-axes particularly easy, with four out of six participants rating each rotation task a score of 7. Moreover, participants reported registering the LEGO space shuttle well, with half ($N=3$) giving it an SEQ score of 7 and all users reporting a 5 or higher.

Additionally, we found concerns regarding utilizing and comprehending some of the app's features. For example, the 'visualization' mode function confused most participants. To use the visualization mode feature, participants must select a desired axis and press the 'V' key on their keyboard. As this was the only app function, not a button on the screen, participants did not instinctively perform this task when asked. Instead, they either returned to the instruction or clicked buttons on the screen to find the visualization mode. These qualitative findings were further highlighted in participants' SEQ scores for changing the visualization mode task as results were mixed, ranging from scores between 4 and 7. Another in-app feature participants did not fully utilize was the "Next" button to change between axes quickly. Participants preferred using the drop-down menu to select the next axis they would use rather than cycle through all the axes or did not realize what the button did when they clicked it.

Finally, based on the review of the SUS post-test measure and the math test accuracy changes from pre-test to post-test, participants in the virtual condition found the AR-Classroom in its starting version low in usability. Before interacting with the AR Classroom, participants had an average matrix algebra pre-test accuracy of 45%, which increased to 55% at the post-test with an increase in confidence ratings from 2.0 to 2.8. These quantitative findings suggest increasing math knowledge and confidence, but this finding should be interpreted cautiously due to the low sample size.

3) *Physical (Workshop 2)*. The results from the physical condition were similar to the virtual in that participants referenced the instructions when needing further guidance on app functionality and instinctively used the dropdown menu to select different axes and pull up different matrices. Participants shared similar frustrations with the reversed view image and registration or tracking issues. They did not efficiently utilize the visualization mode exhibited by mixed ratings on "ease of use." However, there were crucial differences between experiment conditions. Physical condition participants reported that registering the model after discoverability was overwhelmingly high (i.e., easy to complete), with over half (N=4) rating it a 7. The participants in the physical condition also found performing rotations along the Z-axis more complex than the X- and Y-axes, with most participants reporting an SEQ score for the task lower than 5. This issue is likely due to the loss of tracking disrupting the participants' experience, as the wireframe was very shaky and frequently unregistered for multiple participants. However, this may also be due to some participants rotating on a different axis than was selected in the dropdown menu. For example, participants needed to become more familiar with 3D rotations, causing most participants to struggle when asked to complete a Z-axis rotation.

Like the virtual condition participants, the post-test measures and pre- to post-test results indicated that participants in the physical condition rated the AR-Classroom in its starting version as low in usability. However, changes were identified from pre- to post-test matrix algebra accuracy. Physical condition participants had an average matrix algebra test accuracy of 52% in the pre-test, which increased to a moderate

accuracy of 59%. Additionally, confidence ratings for these participants rose from 2.6 to 3.6 from pre- to post-test. Once again, these findings suggest increasing math knowledge and confidence but should be interpreted with caution due to the low sample size.

III. RECOMMENDATIONS AND REDESIGN OF THE AR-CLASSROOM APPLICATION

Based on the benchmark usability test thematic analysis, SEQ and SUS scores, and math test accuracy, several recommendations were provided to the development team:

1. Adding additional guidance on LEGO space shuttle model set-up and registration via an instructional video.
2. Restructuring and updating the instructions to reflect how users utilize instructions (Fig 5).
3. Turning 'visualization mode into an on-screen button rather than using the keyboard (Fig 6).

We also noted app features that users found particularly useful. For example, based on user feedback, we recommended keeping drop-down functions and sliders, as participants can easily use functions in the app after reviewing instructions.

Guided by the recommendations, changes were made to the AR Classroom to enhance usability and functionality. Improvements included the recommendations listed above, as well as: 4) Improved registration by fixing bugs for more consistent and faster model registration, 5) Creating a toggle feature that users can click to switch the direction of the Z-axis (Fig 5), and 6) Implementing a false (incorrect) rotation notification in the physical workshop of the app signals to users that they are not performing a rotation around the selected axis, but a wrong axis (Fig 6). For example, if the user selects the Z-axis and then rotates the LEGO space shuttle model about the Y-axis, a red 'False Rotation' warning will appear on the screen. All changes to the AR-Classroom application were incorporated before the updated usability test began.

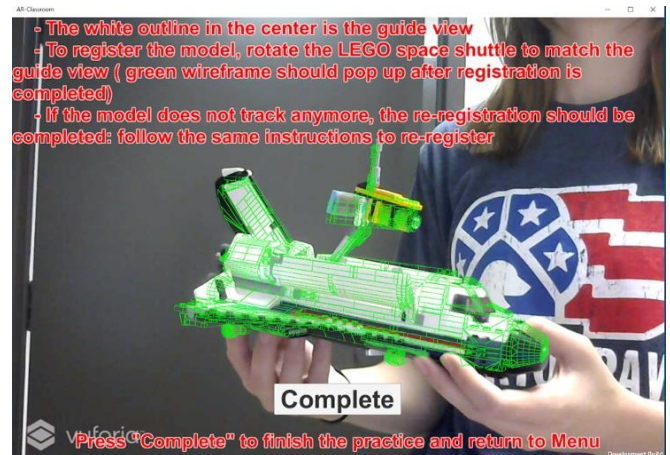


Fig 5. AR-Classroom: Updated condition tutorial model registration.

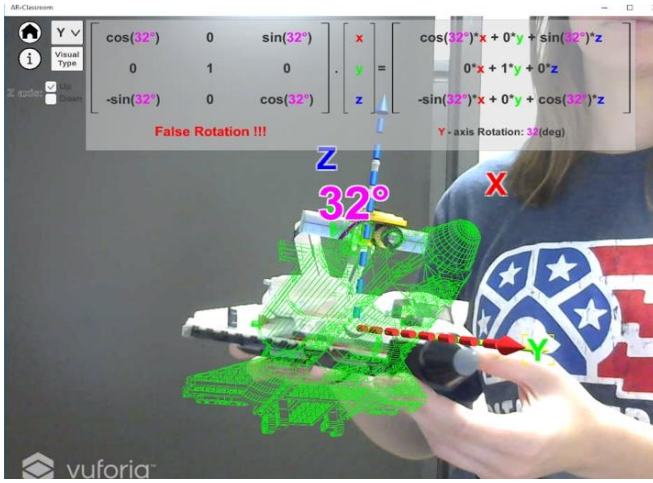


Fig 6. AR-Classroom: Updated condition physical version false rotation on Y-axis.

IV. UPDATED USABILITY TEST

The benchmark usability test assessed usability in the AR-Classroom's original release and recommended improving the app. The updated usability test was then conducted to investigate the effect of the AR-Classroom's changes on the app's discoverability and usability in the virtual and physical workshops of the app. Participants in the updated usability test were recruited using the same methods as the benchmark usability test and received the same amount of research credits after completing the 1-hour experiment. The updated usability participants were twelve undergraduate students at the same public university. In the virtual condition (N=6), participants were primarily 19-year-old freshmen women, most having experience with 2x2 matrices but no experience with 3x3 matrices. In the physical condition (N=6), participants shared the same demographic and previous matrix algebra experiences as the virtual condition participants.

Similar to the benchmark usability test, all participants reported on their previous math experiences, completed a pre-test, watched two videos, interacted with either the virtual or physical workshops of the app, and then provided feedback on their app experience.

A. Methods

The updated usability test participants followed the procedures described in the Benchmark usability methods section. The only modification to the updated usability study procedure included watching a model set-up instructional video on setting up and registering the LEGO space shuttle model when using the AR-Classroom.

B. Model Set-up Instructional Video

Based on the benchmark usability test result, it was determined that the users need more guidance on properly setting up their space shuttle LEGO model for registration. Therefore, a brief tutorial video was created to show users how to properly set up their LEGO model and register it using the AR-Classroom application. Before interacting with either the virtual or physical workshop of AR-Classroom, participants

watched the 1-minute video with the LEGO space shuttle model in front of them to follow along with each step.

C. Results

Similar to the benchmark usability test, thematic analysis results, SEQ and SUS scores, and 3x3 matrix algebra test with confidence ratings were analyzed to examine user-app interactions with the updated version of AR-Classroom (Table 1). In addition, findings from the updated usability test were compared with those of the benchmark test to investigate the impact of AR-Classroom changes on the app's overall usability.

1) *Updated Tutorial model registration.* After creating a LEGO space shuttle model set-up and registration instructional video, there were still mixed reports on "ease of use" (i.e., SEQ score) for registering the LEGO model. Even with video instructions, participants needed help setting up the LEGO space shuttle model correctly to ensure accurate AR tracking. The instructional model set-up video alleviated some frustration with registration. However, additional instructions regarding how the model needs to be set up were needed as some participants still needed help. Additionally, like the benchmark participants, updated test participants needed clarification on the reversed view image, which hindered their experience with the app.

2) *Updated Virtual Workshop.* After discoverability, participants rated model registration favorably, with most SEQ scores (N=4) at six or higher, and reported that the text instructions were practical and useful when unsure how to complete a task using the app. For example, for rotating the model about the Y- or X-axis, all participants (N=6) rated both tasks a 7; for rotation around the X-axis, all but one participant rated the task a 7. The updated usability test participants found performing virtual rotations extremely easy as they knew how to use the dropdown axes to function the rotation angle slider effectively. Moreover, implementing a 'visualization mode' button made the task particularly easy as all participants completed it and rated it a 7 on "ease of use" (SEQ). Participants could quickly locate and use the button to change the visualization mode. However, participants only recognized multiple visualization modes if asked which they preferred, prompting them to pay attention to or recognize the different modes.

Regarding the Z-axis toggle feature to change the Z-axis orientation (pointing up or down as different conventions for different fields, such as robotics or aerospace engineering), participants did not find the function of the toggle button intuitive. As a result, participants initially attempted to change the Z-axis direction using the axis dropdown menu (for selecting the rotation axis) and the angle slider rather than clicking the toggle button. However, once participants completed changing the orientation, all rated the task as six or higher. In a review of the updated participants' SUS post-test measures, participants in the virtual condition found AR-Classroom's updated version to be good in usability. In addition, they had positive changes to math test accuracy and confidence ratings. On average, updated usability test participants in the virtual condition scored 48%

accuracy with a confidence rating of 2.3 on the pre-test math test; at the time of the post-test, math accuracy rose to 57% with a confidence rating of 3.2. This suggests increasing math knowledge and confidence, but this finding should be interpreted cautiously due to the low sample size.

3) *Updated Physical Workshop.* In the updated physical workshop, participants reported similar SEQ scores for registering the LEGO space shuttle model after the discoverability period. Participants still needed some assistance with setting up the model in order to register. However, once a participant was told how to set up the LEGO model correctly, the wireframe registration was immediate. Next, participants would reference the text instructions when they needed to complete a task but did not intuitively know how to do so. After reviewing the updated text instructions, participants could effectively utilize the app's functions, such as navigating and performing the X-, Y-, and Z-axis rotations and changing the visualization mode. In the benchmark test, physical workshop participants struggled with rotating the LEGO space shuttle model about the Z-axis. However, most updated physical workshop participants (N=4) rated the task a 7 on the SEQ score. Participants reported composite scores for reorienting the direction of the Z-axis; however, the thematic analysis revealed that participants were quickly able to change the Z-axis direction but had initial confusion about what the task meant, and the majority noted a preference for the up direction.

Like the participants in the updated virtual workshop, there were noted changes for the participants in the updated physical workshop in math accuracy and confidence ratings from pre- to post-test. For example, participants had an average pre-test math accuracy of 46% that grew to 59% on the post-test, with a confidence rating increase from 2.0 to 2.7. Once again, these findings suggest increasing math knowledge and confidence but should be interpreted cautiously due to the low sample size.

Table 1. AR-Classroom: Benchmark and updated usability test results.

Table 1

AR Classroom: Benchmark and Updated Usability Test Results

Usability Test (N=24)	App Version (Virtual or Physical)	Discoverability* (SEQ average)	SUS	Math Test Accuracy Improvement* (pre to post test)	Math Test Confidence Improvement* (pre to post test)
Benchmark (N=12)	Virtual (N=6)	4.2	58 / 100 D / Poor usability	10%	0.8
	Physical (N=6)	4.5	54 / 100 D / Poor usability	7%	1.0
Updated (N=12)	Virtual (N=6)	5.7	73 / 100 B- / Good usability	9%	0.9
	Physical (N=6)	3.6	63 / 100 C- / Fair usability	13%	0.7

*Note. Due to small sample size statistical significance cannot be inferred.

V. DISCUSSION AND CONCLUSION

The two usability studies examined user-app interactions with AR-Classroom's virtual and physical workshops in the

app's benchmark and updated versions to answer our research questions: 1) What do users discover about the AR-Classroom's tutorial and two workshops? 2) What features of the AR-Classroom are easy versus challenging to use? 3) How do changes made to the AR-Classroom enhance the application's usability for learning 3D matrix algebra? The benchmark usability indicated that users need additional guidance on model set-up and registration, can utilize most of the app's functions effectively, and can quickly complete most tasks using the app with instructions. Based on these results, recommendations were formulated to address issues and enhance users' experience with AR-Classroom. Changes to AR-Classroom applications included reformatting the in-app instructions, creating a corresponding video for guidance on setting up and registering the app's LEGO space shuttle model, restructuring app functions to increase accessibility and enhance utilization, and implementing additional functionality. To investigate the impact of the above-mentioned changes on the AR-Classroom app's usability, an updated usability test was conducted following the same procedures as the benchmark study. The updated usability study revealed that users could effectively use the app's features, perform correct rotations about the X-, Y-, or Z-axis with the app's functions, and found interacting with the app relatively easy. These findings indicate that the AR-Classroom's in-app functions are accessible and intuitive for users and that the changes made to the virtual and physical workshops of AR-Classroom improved usability and enhanced user-app interactions.

Additional major findings from the present study include the following. First, back-to-back usability tests, such as what was conducted in the present study, provide a great way to identify issues and examine the impact of changes made to an application. This approach to usability studies allows researchers to provide app developers with data-driven solutions to usability issues and ensure that fixes are appropriate through qualitative and quantitative analyses.

Second, clear and direct instructions in multiple forms can enhance students' interaction with educational apps. Video instructions for complex educational tools help get students started and provide educators with a reference for troubleshooting user-app issues. Additionally, a quickly accessed text-based instruction page allows users to problem-solve and self-direct their learning experience with the app.

Third, implementing AR technology into educational settings provides a more accessible tool or medium to give students multiple sources of stimulation. As there were no challenges beyond the AR registration process, the present study highlights that AR can help learn the subject (spatial transformations and their matrix representation) when the technology is easy to use and offloads cognitive processes, such as mental rotation, which can be challenging for many students.

Finally, exploration of a new app before starting the educational content is essential as students learn what is available without the burden of trying to learn new materials. By providing structured time for students to become familiar with the application, they can later solely focus on the learned content rather than trying to figure out app functionality and content simultaneously.

VI. LIMITATIONS AND FUTURE RESEARCH

Combining thematic analysis methodology with quantitative measures (i.e., SEQ and SUS scores, and math test accuracy and confidence measures) allowed us to investigate undergraduate students' experience interacting with and usability of the starting version (i.e., benchmark) and the updated version of the AR-Classroom, which was a major strength of this work. However, several limitations impact the broader conclusions drawn from the data. First, the study's small sample size limits the ability to determine any statistical significance of the quantitative measures and further limits the generalizability of the findings. However, the smaller sample size allowed for a deeper analysis of users' qualitative experiences using AR-Classroom. Next, our study mainly consisted of psychology undergraduate female students' interactions with AR-Classroom. However, the app aims to be used across STEM undergraduate education for all genders. Future usability studies on AR-Classroom and other educational technologies alike should intentionally recruit participants across disciplines and identities to ensure that their application is accessible to and effective for a variety of learners.

In conclusion, this paper reviewed two usability tests. The benchmark usability test investigated the usability of the AR-Classroom app's virtual and physical workshops in its standard condition. Then, an updated usability test investigated the impact of changes made based on the benchmark study's findings. Changes in discoverability, usability, and quantitative measures between the benchmark and updated version of the app were further discussed in the context of incremental changes. The findings from the present study can guide future research on the usability of the AR-Classroom app and for the development and usability of other educational technologies, including AR, for STEM education.

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