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Original Research

Design of an Augmented Reality Learning Application for Three-Dimensional Trigonometry Using Marker-Based Tracking

Nurul Zakiah [a], Khairunnisa [b*]

[a,b]Department of Informatics Engineering, Faculty of Engineering and Computer Science, Universitas Harapan Medan, Medan, Indonesia

*Corresponding Author: khairunisa150197@gmail.com

ABSTRACT

Three-dimensional trigonometry requires students to understand relationships among points, lines, planes, distances, and angles in spatial objects, yet conventional two-dimensional explanations often provide insufficient visual support. This study designed and evaluated an Android-based augmented reality learning application using marker-based tracking to present interactive models of a cuboid, cube, triangular prism, and pyramid. The application was developed with Unity 2022 LTS, Vuforia SDK, C#, and Blender. Its functions include marker scanning, three-dimensional object visualization, explanatory content, an interactive quiz, score feedback, usage guidance, and printable flashcard markers. Functional testing used eleven black-box scenarios on two Android devices, while user evaluation involved 20 students who completed a ten-item questionnaire. All functional scenarios produced the expected output, resulting in a 100% success rate. The Vuforia image targets achieved a four-star rating; the effective detection distance was 17–50 cm, with usable viewing angles between 45 and 90 degrees. Student evaluation produced an average score of 95.1%, classified as good according to the study criteria. The findings indicate that marker-based augmented reality can provide stable spatial visualization, straightforward navigation, and an engaging supplementary medium for learning three-dimensional trigonometry. Future development should expand the learning material, increase the question bank, optimize performance on lower-specification devices, and examine markerless tracking.

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1 INTRODUCTION

Digital learning media can strengthen student engagement by combining text, graphics, animation, and interactive control within a single learning environment [1]. In mathematics education, this capability is particularly important for spatial topics because students must coordinate numerical procedures with mental representations of three-dimensional objects. Studies of solid geometry report persistent difficulties in identifying projections, auxiliary triangles, distances, and angles when instruction relies primarily on static diagrams [2, 3].

Augmented reality (AR) addresses this visualization problem by superimposing virtual objects on the physical environment through a mobile camera. In marker-based implementations, a printed image target supplies a stable spatial reference that enables the system to estimate position and orientation before rendering a three-dimensional model. Previous work has applied marker-based AR to elementary geometry and solid-figure learning, reporting improved interaction, spatial understanding, and high usability [4, 5]. Android-based AR has also been used to present three-dimensional mathematical objects as supplementary learning material [6]. Existing studies establish the educational value of AR, but many applications focus on general geometry, science, or introductory solid figures rather than three-dimensional trigonometry. A prior solid-geometry application developed with Unity obtained strong feasibility results [7] and other Unity-based AR studies confirm that mobile devices can integrate three-dimensional assets and contextual explanations effectively [8]. However, trigonometry requires an additional connection between spatial models, labelled sides, angles, formulas, worked solutions, and assessment activities.

The novelty of this research lies in the seamless integration of interactive spatial visualization and a formative assessment module specifically tailored for three-dimensional trigonometry, an area that remains underexplored in existing Augmented Reality (AR) literature. Unlike previous AR studies that predominantly focus on basic 3D shape recognition or general science concepts, this study uniquely bridges the gap between virtual spatial models and mathematical reasoning within a single, offline mobile workflow. The system's distinctiveness is further enhanced by the use of physical flashcards as image targets, which serve not merely as tracking markers, but as concrete interaction points that anchor virtual models to the physical environment. This holistic approach offers a practical, empirically validated solution to overcome students' difficulties in spatial abstraction, thereby filling a critical gap in the literature regarding AR applications that are not only visually engaging but also evaluative and contextually grounded for advanced mathematics education [17–19].

To realize this conceptual framework, this study developed an offline Android application that combines marker-based tracking, four spatial models, explanatory material, a five-question quiz, score feedback, usage guidance, and printable flashcard markers. The work was directed toward two objectives: designing a functional AR learning application for three-dimensional trigonometry and determining its feasibility from functional-test results and student responses [20]. The study does not measure long-term learning gain and does not compare marker-based tracking with markerless AR.

2 RESEARCH METHODS

2.1 Research Design and Participants

The research used an applied development design consisting of problem analysis, requirement specification, system modelling, interface design, three-dimensional asset production, application implementation, functional testing, and user evaluation. The target users were students studying trigonometry. Functional verification was conducted by the developer and independent testers, while the feasibility evaluation involved 20 student respondents after they had used the application.

2.2 System Requirements and Architecture

The application was specified for Android 7.0 or later, a minimum of 2 GB RAM, a 5 MP autofocus camera, a quad-core processor, and approximately 150 MB of free storage. The application operates offline after installation. Its main modules are the primary menu, secondary menu, AR camera, object explanation, quiz, score page, guide, audio control, and exit function.

The development architecture starts with construction and texturing of the spatial objects in Blender. The models are exported in FBX format and imported into Unity, where the user interface, scripts, animation, and learning content are assembled. Vuforia supplies the marker database and tracking engine. During use, the student directs the camera toward a registered flashcard; the system detects the target and renders the corresponding object above it. Figure 1 presents the development architecture together with the operational application flow.

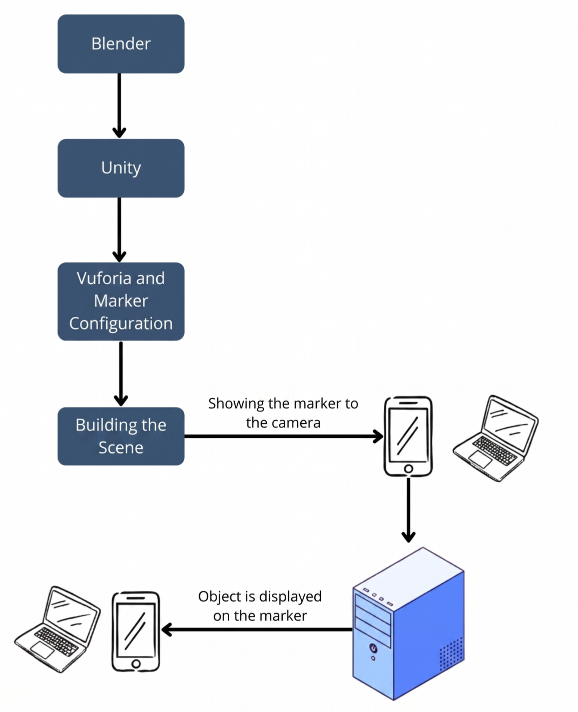

Figure 1. System-development architecture and application workflow

2.3 Application and Three-Dimensional Asset Development

Unity 2022 LTS was used as the application engine and C# was used to control navigation, quiz logic, score calculation, audio, and scene transitions. Unity is widely used for interactive learning because it integrates two-dimensional interfaces, three-dimensional objects, scripts, and mobile deployment within one project [9,10]. Blender was used to construct the cuboid, cube, triangular prism, and pyramid; its modelling and export functions support the production of reusable educational assets [11]. Vuforia SDK was integrated as the image-target tracking component because it provides marker recognition and pose estimation within Unity [12].

2.4 Marker-Based Tracking Procedure

The tracking process consisted of five stages. First, the Android camera captured a continuous image stream at approximately 24 frames per second. Second, each frame was prepared for feature detection. Third, Vuforia compared natural feature points in the frame with the registered image-target database. Fourth, after a match was found, the system estimated translation and rotation relative to the camera and generated a 4×4 transformation matrix. Fifth, Unity used the transformation to render the three-dimensional object synchronously with marker movement. This sequence produced the visual impression that the virtual object remained attached to the physical flashcard.

2.5 Functional and User Evaluation

Black-box testing examined the externally observable behaviour of the system without inspecting source-code structure, which is appropriate for verifying user-facing application functions [13,14]. Eleven scenarios covered application launch, menu navigation, marker detection, operation without a marker, marker movement, low-light conditions, audio, quiz execution, guidance, back navigation, and application exit. Tests were performed on an iQOO Z10 5G and an Infinix Note 50 Pro, both running Android 16 with 50 MP cameras. Each scenario was repeated at least three times. Recent software-testing research also identifies functional black-box evaluation as an important component of extended-reality quality assurance [15].

The student questionnaire contained ten statements grouped into interface quality, usefulness, learning value, information clarity, and comfort. Responses were summarized with a percentage calculation: observed score divided by the maximum possible score, multiplied by 100%. The study used three categories: less than 50% = poor, 51%–80% = sufficient, and 81%–100% = good.

$$P = \left(\frac{\text{observed score}}{\text{maximum score}}\right) \times 100\% \tag{1}$$

3 RESULTS AND DISCUSSION

3.1 Application Interface Implementation

The application interface is designed with a focus on usability and clear navigation to ensure students can operate it independently. The workflow begins with a splash screen, followed immediately by the Main Menu. This initial screen is designed with a portrait layout and large, distinct buttons to facilitate smooth operation on smartphones. The visual theme incorporates 3D geometric shapes to immediately contextualize the subject matter. Figure 2 displays the visual structure of the Main Menu and the subsequent Secondary Menu.

Figure 2. Main and secondary application menus

As shown in Figure 2 (left), the Main Menu features the application title 'TRIGONOMETRI' set against a dark background. It provides three primary options: 'Masuk' (Start) to begin the learning session, 'Panduan' (Guide) for instructions on how to use the application, and 'Keluar' (Exit) to close the program. An audio toggle icon is also visible in the top right corner for sound control. When the user selects 'Masuk', the application navigates to the Secondary Menu (Figure 2, right). This screen, distinguished by an orange background, offers the two core functional modules: 'AR Kamera' for accessing the augmented reality visualization and 'Kuis' for testing understanding. A home button in the top left allows users to return to the Main Menu at any time, ensuring flexible navigation.

3.2 Augmented-Reality Learning Display

When a student scans a registered flashcard marker, the application renders the corresponding three-dimensional object in real-time. The AR display presents not only the spatial model but also contextual trigonometric problems related to the object. Each visualization includes labeled dimensions, angles, and geometric relationships that students need to analyze. Figure 3 illustrates the AR camera output showing a pyramid (limas) visualization alongside its detailed explanation panel.

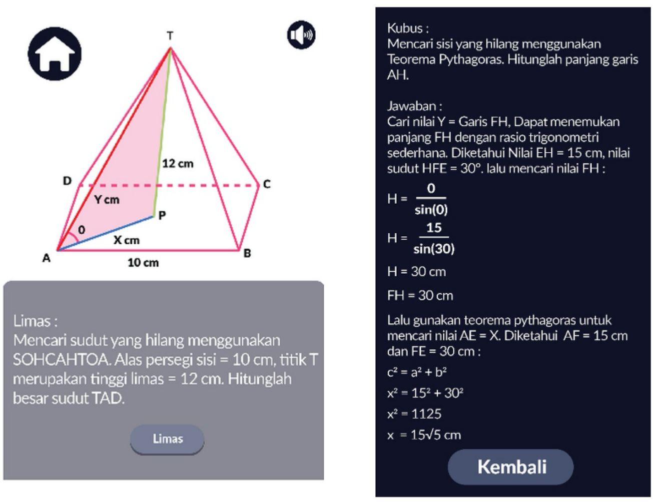

Figure 3. Marker-based AR visualization and object explanation

Figure 3 illustrates the dual-screen interface of the learning application, which integrates the augmented reality visualization with the step-by-step explanatory content. The left side of Figure 3 displays the AR camera view where a virtual pyramid is rendered over the physical marker. This scene presents a contextual trigonometric problem, such as finding a missing angle using SOHCAHTOA, complete with labeled vertices (A, B, C, D, T), known dimensions (10 cm base, 12 cm height), and variables to be solved (X cm, Y cm, and angle θ). The right side of Figure 3 shows the detailed solution page that appears when the user accesses the explanation. It provides the mathematical reasoning, including the application of trigonometric ratios (e.g., calculating a length using the sine function) and the Pythagorean theorem to derive the final value (e.g., $x = 15\sqrt{5}$ cm). By separating the spatial visualization from the algebraic calculation, this design helps students systematically connect the 3D model with the abstract mathematical formulas required to solve the problem.

3.3 Interactive Quiz and Guidance

Beyond visualization, the application incorporates an interactive assessment module and a comprehensive user guide to support independent learning. The quiz module is designed to test the student's understanding of the trigonometric concepts presented in the AR scenes, while the guide ensures they can operate the AR camera effectively without external assistance. Figure 4 illustrates the interfaces for the quiz questions, the scoring feedback, and the step-by-step usage instructions.

Figure 4. Quiz, score, and usage-guidance interfaces

Figure 4 details the three key support screens of the application. The left panel displays the quiz interface, presenting a multiple-choice question in Indonesian regarding the angle between a space diagonal and an edge of a cube ('Sebuah kubus ABCD.EFGH...'). The answer options include mathematical expressions, such as $\cos^{-1}(1/3)$, requiring students to apply trigonometric formulas rather than simple estimation. The middle panel shows the feedback screen, which displays the final accumulated score (e.g., 'Skor/5') and provides a 'Ulang' (Repeat) button, allowing students to retry the quiz for self-improvement. The right panel presents the 'Cara Menggunakan AR Kamera' (How to Use the AR Camera) guide. It lists four clear steps: preparing the marker, activating the camera via the menu, aiming the camera at the marker, and waiting for the 3D object to render. This structured guidance minimizes technical confusion, ensuring students can focus on the learning material.

3.4 Marker Design and Tracking Performance

A critical component of the marker-based AR system is the design of the image targets, which must contain sufficient visual features for Vuforia to detect and track reliably. Four distinct flashcard markers were created, each corresponding to one of the three-dimensional objects in the application: a cuboid (balok), a cube (kubus), a triangular prism (limas segitiga), and a pyramid (limas). Each marker combines a central geometric illustration with a repeated textual pattern to maximize the number of detectable feature points. Figure 5 presents the four flashcard markers used in the application.

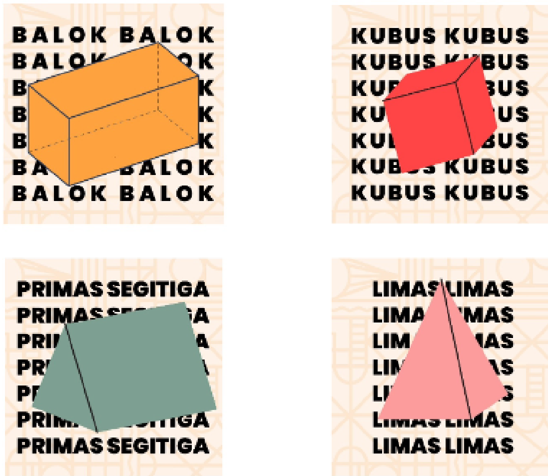

Figure 5. Flashcard markers for the four three-dimensional objects

Figure 5 displays the four image targets designed for the application, each featuring a unique color scheme and repeated label to ensure distinguishability during tracking. The top-left marker represents the cuboid (Balok), illustrated in orange with the word 'BALOK' repeated across a light background. The top-right marker depicts the cube (Kubus) in red, surrounded by the repeated text 'KUBUS'. The bottom-left marker shows the triangular prism (Primas Segitiga) in green with the label 'PRIMAS SEGITIGA' repeated, while the bottom-right marker presents the pyramid (Limas) in pink with the text 'LIMAS' filling the background. The repeated textual patterns serve a dual purpose: they reinforce the terminology of each shape for the student, and they provide Vuforia with a high density of natural feature points, which improves tracking stability and reduces the likelihood of false detection between markers. All markers were printed on yellow board at a minimum resolution of 300 DPI to maintain image clarity under the camera.

To ensure reliable tracking performance, the physical flashcards must meet specific technical requirements. The Vuforia SDK evaluates image targets based on contrast, detail, and feature distribution, assigning a star rating from one to five to indicate their detectability. The markers developed in this study were carefully designed and tested to determine their optimal physical and operational parameters. Table 1 summarizes the technical specifications and tracking constraints of the AR markers used in the application.

Table 1. Technical specifications of the AR markers

Parameter	**Specification**
Optimal marker size	19 cm × 20 cm
Optimal detection distance	17–50 cm from the camera
Maximum practical distance	Less than 60 cm; above this range the object becomes unstable
Detection angle	45–90 degrees relative to the perpendicular marker axis
Print medium	Yellow board
Minimum print resolution	300 DPI
Vuforia marker rating	4 of 5 stars
Target type	Image Target

As presented in Table 1, the Vuforia Image Target tool awarded the markers a rating of 4 out of 5 stars, indicating a strong distribution of detectable visual features. The optimal detection distance was established between 17 cm and 50 cm. When the camera is positioned beyond 60 cm, the tracking becomes unstable or fails entirely due to a loss of feature resolution. Furthermore, the detection angle is constrained between 45 and 90 degrees relative to the perpendicular axis; extreme viewing angles cause the virtual object to jitter or disappear. The use of a yellow board with a minimum print resolution of 300 DPI ensures sufficient contrast and sharpness, which are critical for the Vuforia engine to maintain a consistent frame rate and accurate pose estimation. Under normal lighting, the system displayed the object within slightly more than one second after the marker entered the camera view, confirming the markers' operational readiness.

3.5 Black-Box Testing Results

To verify the functional reliability of the application, black-box testing was conducted to evaluate the system's external behavior without inspecting the internal source code. The testing encompassed eleven distinct scenarios covering the entire user workflow, including application launch, menu navigation, AR camera activation, marker interaction, environmental constraints (such as low light and no-marker conditions), audio control, quiz execution, and application exit. These tests were performed repeatedly on two Android devices (iQOO Z10 5G and Infinix Note 50 Pro) to ensure cross-device consistency [21]. Table 2 summarizes the test actions, expected outputs, observed results, and the final validation status for each feature.

Table 2. Black-box testing results

No.	Feature	Test action	Expected output	Observed	Status
1	Application launch	Tap the application icon	Main menu appears completely	Successful	Valid
2	Start button	Tap Start	Secondary menu appears	Successful	Valid
3	AR camera	Open AR Camera	Camera and AR scene become active	Successful	Valid
4	No marker	Point camera at an empty surface	No 3D object appears	Successful	Valid
5	Moving marker	Move marker slowly	3D object follows the marker	Successful	Valid
6	Low light	Scan marker in reduced lighting	Marker is detected with lower stability	Successful	Valid
7	Audio	Toggle the audio control	Audio switches on or off	Successful	Valid
8	Quiz	Start and answer the quiz	Questions and options appear; score calculated	Successful	Valid
9	Guide	Open the guide	Instruction page appears	Successful	Valid
10	Back navigation	Use Back on each page	Previous page opens without error	Successful	Valid
11	Exit	Tap Exit	Application closes normally	Successful	Valid

As detailed in Table 2, all eleven functional scenarios produced outputs that perfectly matched the expected behavior, resulting in a 100% validation success rate. The application successfully handled standard navigation flows, such as launching the main menu, accessing the AR camera, and executing the quiz module without any crashes or navigation errors. Crucially, the system also responded correctly to edge-case and environmental conditions. For instance, in the 'No marker' scenario, the application correctly refrained from rendering any 3D object when pointed at an empty surface, preventing visual glitches. In the 'Low light' scenario, the system successfully detected the marker but exhibited the expected reduction in tracking stability; this was classified as 'Valid' because it reflects the natural physical limitations of image-based tracking rather than an application defect. Furthermore, the 'Moving marker' test confirmed that the 3D objects remained anchored and smoothly followed the physical flashcard in real-time. The flawless execution across all test cases confirms that the application is functionally robust and ready for supervised classroom deployment.

3.6 Student Evaluation

To assess the feasibility and user acceptance of the developed application, a user evaluation was conducted involving 20 students who had actively used the application. The evaluation utilized a questionnaire containing ten statements covering key aspects such as interface quality, visual design, learning appeal, educational usefulness, and overall comfort. The responses were quantified using a percentage scale to determine the overall suitability of the application as a learning medium. Table 3 presents the detailed results of the student evaluation across all ten aspects.

Table 3. Student evaluation results

No.	Evaluation aspect	Percentage
1	Interface clarity	95%
2	Color/background	90%
3	Learning appeal	100%
4	Supports learning	100%
5	3D object fidelity	90%
6	AR display clarity	93%
7	Learning suitability	100%
8	Information clarity	93%
9	Content sequence	90%
10	Overall comfort	100%
Average		**95.1%**

As shown in Table 3, the application received highly positive feedback from the students, achieving an overall average score of 95.1%, which falls into the 'good' category according to the study's criteria. Four specific aspects achieved a perfect score of 100%: learning appeal, support for the learning process, learning suitability, and overall comfort. These results indicate that students found the application not only engaging but also highly relevant and helpful for understanding three-dimensional trigonometry. The lowest recorded score was 90%, observed in aspects such as color/background suitability, 3D object fidelity, and content sequence. While slightly lower than the perfect scores, these values still reflect a very high level of user satisfaction. Furthermore, the high scores in interface clarity (95%), AR display clarity (93%), and information clarity (93%) confirm that the application's design effectively communicates the learning material without causing confusion. Overall, the evaluation demonstrates that the marker-based AR application is a highly acceptable and effective supplementary tool for mathematics education.

The quantitative results from the questionnaire are further visualized to provide a clearer comparison of student perceptions across different evaluation aspects. This graphical representation highlights the distribution of scores and makes it easier to identify which features of the application were most appreciated by the students. Figure 6 presents a horizontal bar chart illustrating the percentage scores for each evaluation aspect from the student evaluation of the AR trigonometry application.

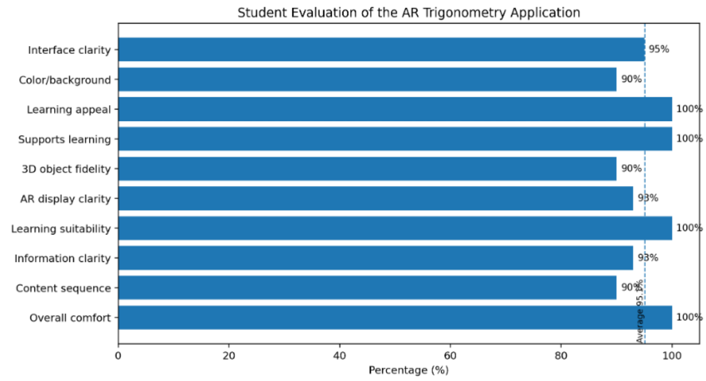

Figure 6. Percentage results of the student evaluation

Figure 6 visually confirms the consistently high ratings across all ten evaluation aspects, with all bars extending well beyond the 90% threshold. The chart clearly shows four aspects reaching the maximum score of 100%: learning appeal, supports learning, learning suitability, and overall comfort. These perfect scores are represented by bars that extend fully to the right edge of the chart, indicating unanimous positive responses from all 20 student respondents. The vertical dashed line at 95.1% represents the overall average score, serving as a visual benchmark [4, 5]. Most evaluation aspects scored at or above this average, demonstrating that the application performed exceptionally well across multiple dimensions. The aspects scoring 90% (color/background, 3D object fidelity, and content sequence), while technically the lowest, still represent excellent user satisfaction and suggest only minor areas for potential refinement. The visualization effectively demonstrates that students perceived the application as highly engaging, educationally valuable, and comfortable to use, which aligns with the study's objective of creating an effective supplementary learning tool for three-dimensional trigonometry. They are also consistent with research showing that three-dimensional digital representations can support geometry learning when students experience difficulty interpreting static spatial diagrams [16].

3.7 Discussion

The primary contribution of this study lies in the successful integration of interactive spatial visualization and formative assessment within a single, offline mobile workflow for three-dimensional trigonometry. The 100% functional success rate and the 95.1% positive student evaluation demonstrate that the application effectively bridges the gap between abstract mathematical formulas and concrete spatial representations. Unlike previous AR studies that primarily focus on the mere visualization of basic 3D shapes, this application uniquely embeds worked solutions and an interactive quiz directly into the learning sequence. This holistic approach ensures that students do not merely observe the geometry but actively engage with the trigonometric reasoning required to solve problems, thereby addressing the persistent cognitive difficulties associated with interpreting static diagrams in solid geometry.

From a technical perspective, the results validate the practical trade-offs of marker-based tracking in educational settings. The four-star Vuforia rating and the stable detection within the 17 to 50 cm range confirm that the designed flashcards, with their high-contrast repeated textual patterns, provide sufficient natural feature points for reliable pose estimation. This stability is crucial for maintaining student engagement, as tracking failures can quickly lead to cognitive overload and frustration. However, the observed decrease in stability under low-light conditions or at extreme viewing angles highlights an inherent limitation of image-target methods. This finding underscores the importance of environmental control in classroom deployments and suggests that while marker-based tracking is computationally efficient and highly reliable on mid-to-high-end devices, it requires careful instructional scaffolding regarding proper device handling and adequate lighting.

These findings strongly align with and extend existing literature on technology-enhanced mathematics education.

Previous research has established that AR can improve spatial understanding and usability in elementary geometry; this study extends that validity to the more complex domain of three-dimensional trigonometry. The dual-panel design, which separates the interactive 3D visualization from the algebraic calculation steps, directly supports cognitive load theory by preventing students from being overwhelmed by simultaneous visual and numerical processing. By allowing learners to manipulate the physical marker to inspect the object from multiple viewpoints before consulting the step-by-step mathematical derivation, the application fosters a deeper, self-paced conceptual understanding that static textbooks cannot provide.
Despite these promising results, several limitations must be acknowledged to guide future research. First, the current evaluation measures perceived usability and functional feasibility rather than objective, long-term learning gains; therefore, the high satisfaction scores should not be automatically equated with improved academic performance without further experimental validation. Second, the application is currently limited to four specific spatial models and a small question bank, which may restrict its comprehensiveness for extended curriculum use. Future work should address these limitations by expanding the library of 3D trigonometric models and assessment items, conducting rigorous quasi-experimental studies to measure actual learning outcomes, and exploring the integration of markerless tracking or plane detection to eliminate the dependency on printed flashcards and enhance the seamless blending of virtual and physical learning environments.

4 CONCLUSION

This study successfully developed and evaluated an Android-based augmented reality application for three-dimensional trigonometry using marker-based tracking. The integration of Unity 2022 LTS, Vuforia SDK, C#, and Blender produced a functional learning tool that combines marker scanning, four interactive three-dimensional objects (cuboid, cube, triangular prism, and pyramid), explanatory material with worked solutions, a five-question quiz with score feedback, usage guidance, and printable flashcard markers. All eleven black-box testing scenarios were validated successfully, achieving a 100% functional success rate across both test devices. The AR markers received a four-star rating from Vuforia, with optimal detection performance at distances of 17–50 cm and viewing angles between 45–90 degrees. The student evaluation involving 20 respondents yielded an average score of 95.1%, classified as "good," with perfect scores in learning appeal, learning support, learning suitability, and overall comfort. These results confirm that the application is feasible and highly acceptable as a supplementary visualization and practice medium for three-dimensional trigonometry. The study demonstrates that marker-based AR can effectively bridge the gap between spatial visualization and mathematical reasoning, providing students with an engaging tool to overcome difficulties in interpreting three-dimensional geometric relationships. Future development should focus on expanding the learning content and question bank, optimizing performance for lower-specification devices, conducting experimental studies to measure actual learning outcomes, and exploring markerless tracking technologies to enhance flexibility and reduce dependency on physical markers.

DECLARATIONS

Author Contributions:
Nurul Zakiah: Conceptualization, Methodology, Software, Writing – Original Draft.
Khairunnisa: Data Curation, Validation, Visualization, Writing – Review & Editing.

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Data Availability:
The data that support the findings of this study are available from the corresponding author upon reasonable request.

AI Use Statement:
During the preparation of this work, the authors used ChatGPT in order to improve the language and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the final content of the published article.

Additional Information:
No additional information is available for this paper.

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