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Development of an Augmented Reality–Based Geometry Module to Enhance Students' Understanding of Three-Dimensional Concepts

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ABSTRAK

This study aims to develop and evaluate an Augmented Reality (AR) based geometry module intended to improve students' understanding of three dimensional (3D) concepts. The research responds to the persistent challenges students face in visualizing geometric solids and interpreting spatial relationships, which commonly result in misconceptions in geometry learning. A research and development (R&D) approach was applied to 126 junior high school students selected through cluster sampling. Data were gathered using pre-tests, post-tests, spatial ability assessments, and motivation questionnaires, supported by classroom observations. The results revealed a significant increase in students' conceptual understanding and spatial reasoning after using the AR-based module. Students also demonstrated higher motivation and engagement throughout the learning process. Data analysis indicated strong effect sizes and substantial normalized gains, confirming the effectiveness of AR in enhancing 3D geometry comprehension. The AR module succeeded in transforming abstract geometric content into interactive and concrete representations, thereby supporting meaningful learning. This study concludes that AR is a promising tool for improving both cognitive and affective learning outcomes in mathematics.

INTRODUCTION

Students' difficulty in comprehending three-dimensional (3D) geometry remains a widely recognized issue in mathematics education and continues to be one of the most persistent learning challenges across grade levels. Numerous studies report that students struggle to mentally visualize geometric solids, identify and distinguish spatial features, and interpret abstract representations of objects, resulting in recurring misconceptions and low performance in geometry-related tasks (Lestari & Dafik, 2025; Gunawan et al., 2025). These difficulties are magnified by learners' limited exposure to dynamic or manipulable geometric models, which makes the transition from two-dimensional textbook diagrams to actual three-dimensional structures cognitively demanding. Preliminary observations conducted in several junior high schools reinforce this concern: more than 65% of students were unable to meet the minimum mastery criterion on assessments involving mental rotation, spatial relation analysis, and surface-area reasoning. Such findings are consistent with broader international research, which identifies deficits in spatial visualization as a major contributor to conceptual errors in geometry learning (Méndez & Avilés, 2025; Freina & Ott, 2020; Suryaningrum et al., 2023).

Several factors underpin these recurring learning difficulties. Traditional learning media such as printed diagrams, static images, or simple wooden models lack the flexibility to fully represent the complexity of geometric solids. Students cannot rotate, decompose, or reconfigure these objects freely, which limits their ability to explore structural relationships and develop accurate mental imagery (Ibáñez & Delgado-Kloos, 2018). Cognitive theories also suggest that abstract concepts in geometry require high mental load when learners rely solely on static representations, ultimately overwhelming working memory and hindering reasoning processes (Sweller et al., 2019). This theoretical explanation aligns with empirical evidence highlighting that students often misinterpret hidden surfaces, struggle with perspective-taking, and fail to connect symbolic formulas to spatial meaning (Bacca et al., 2021; Freina & Ott, 2020).

Technological innovation particularly Augmented Reality (AR) has introduced new possibilities for overcoming these long-standing challenges. AR enables students to interact with digital 3D objects overlaid onto the real world, making abstract geometric forms more tangible, manipulable, and visually intuitive (Rohendi et al., 2025; Chonchaiya & Srithammee, 2025). Through AR, learners can rotate, zoom, dissect, and reassemble geometric solids directly, thereby strengthening conceptual connections and reducing reliance on mental visualization alone. Research consistently affirms that AR improves conceptual comprehension, supports cognitive processing of spatial relationships, and enhances mental rotation ability due to its immersive and multimodal visualization capabilities (Gargrish et al., 2021; Gargrish et al., 2022; Nadzri et al., 2023). Recent meta-analyses further highlight that AR significantly enhances learner engagement, reduces cognitive load, and improves motivation in STEM education contexts (Sirakaya & Cakmak, 2020; Radu, 2014; Bacca et al., 2021).

Despite these promising developments, the majority of AR-based learning studies remain focused on application-level features rather than on systematically developed instructional modules integrated with curriculum requirements. Many AR tools are designed as supplementary visual aids rather than pedagogically grounded learning modules that incorporate structured objectives, task sequencing, and assessment components. As a result, there is limited empirical evidence concerning AR interventions that are deliberately aligned with formal classroom instruction or responsive to documented learner difficulties. Furthermore, only a small number of studies have systematically evaluated AR modules specifically tailored for 3D geometry at the junior high school level, even though strong evidence indicates AR's potential to transform spatial learning (Husna et al., 2025; Putri et al., 2025). The scarcity of studies integrating AR with conventional learning sequences such as guided inquiry, reflective tasks, or formative evaluation reveals a research gap and a compelling opportunity for more pedagogically robust AR implementations (Teixeira & Alessio, 2024; Sarkar et al., 2020).

This research addresses these gaps by developing an AR-based geometry module aligned with national curriculum standards and structured into coherent learning components, including concept exploration, guided tasks, reflective questions, and formative assessments. Unlike many AR applications that function merely as visualization tools, this module is explicitly designed to serve as a full instructional unit capable of improving cognitive outcomes while simultaneously enhancing student engagement. The novelty of this study lies in integrating AR technology within a structured pedagogical framework and conducting a comprehensive evaluation of its impact on students' 3D conceptual understanding, spatial ability, and motivation. Supported by recent empirical findings that emphasize AR's role in elevating both cognitive and affective learning dimensions, this study contributes a systematic, evidence-based approach to embedding AR into mathematics instruction.

Accordingly, the objective of this research is to develop and evaluate the effectiveness of an Augmented Reality–based geometry module in enhancing students' understanding of three-dimensional concepts, improving their spatial reasoning skills, and increasing their learning motivation.

METHODOLOGY

This study employed a research and development (R&D) methodology adapted from the Plomp model, consisting of preliminary investigation, design, development, implementation, and evaluation. The population consisted of junior high school students, and 126 participants were selected via cluster sampling from three schools. Data were collected using pre-tests and post-tests on 3D geometry concepts, a spatial ability test, classroom observations, and student motivation questionnaires. Expert validation sheets were used during the development stage to evaluate material accuracy and media usability. Quantitative data were analyzed using paired sample t-tests, effect size (Cohen's d), and normalized gain scores, while qualitative data from observations and responses were analyzed descriptively to enrich interpretation of results.

To guide the systematic development of the AR-based module, the research employed a structured Research and Development (R&D) model adapted from the Plomp framework. The methodology was designed to ensure that each stage of the development process strengthened the instructional quality of the resulting module. Before presenting the main empirical findings, it is essential to outline the sequential steps undertaken in the study, as these stages collectively ensured alignment between curriculum needs, technological design, and pedagogical objectives.

Gambar 1. Research Procedure Flow

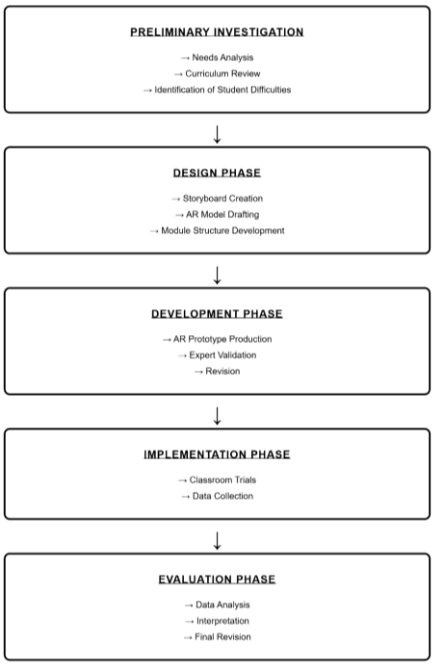

Figure 1 presents a structured overview of the research procedure, depicting the systematic flow of activities undertaken throughout the development and evaluation of the AR-based geometry module. The diagram outlines five major phases, each contributing an essential layer of rigor to the overall research process. The preliminary investigation phase served as the foundation by identifying core student difficulties, examining curriculum competency standards, and analyzing gaps in existing instructional materials. This step ensured that the module addressed authentic classroom needs rather than hypothetical or assumed challenges.

The design phase transformed these preliminary insights into concrete instructional plans. During this stage, researchers produced detailed storyboards, outlined learning pathways, selected appropriate AR interactions, and drafted the pedagogical structure of the module. This ensured that the AR features were not merely technological add-ons, but fully embedded within a coherent learning sequence that aligned with curriculum expectations.

Next, the development phase focused on constructing the AR prototype and refining it through expert validation. Iterative reviews by subject-matter experts, media specialists, and instructional designers helped improve the accuracy, clarity, and usability of both the AR interface and the accompanying learning materials. Revisions during this phase strengthened the module's alignment with both instructional goals and technological best practices.

The implementation phase introduced the refined module into real classroom settings. During this stage, students interacted directly with the AR features, and data were collected through tests, observations, and questionnaires. This phase was crucial for capturing authentic learning behaviors, identifying practical challenges, and assessing the module's effectiveness under genuine instructional conditions.

Finally, the evaluation phase involved analyzing and synthesizing the quantitative and qualitative data collected during implementation. This allowed researchers to determine the module's impact on student learning, identify strengths and limitations, and make necessary revisions to enhance its instructional value. This concluding phase also ensured that the findings were evidence-based and aligned with the study's objectives.

Overall, Figure 1 highlights a research process that is both systematic and iterative, ensuring methodological rigor and internal coherence. The sequential structure demonstrates how each phase informed the next, ultimately producing a well-developed and pedagogically sound AR-based geometry module.

RESULTS AND DISCUSSION

The results of this study are presented by categorizing the observed improvements into three primary dimensions: understanding of 3D geometric concepts, enhancement of spatial ability, and student motivation. Each dimension is supported by quantitative evidence obtained from pre-tests, post-tests, and survey instruments. Tables are presented to summarize the statistical trends, followed by a bar chart that visually reinforces the magnitude of change across learning indicators. The following subsections detail these findings comprehensively.

A. Improvement in Students' Understanding of 3D Geometry Concepts

The analysis revealed a substantial increase in students' conceptual understanding after using the AR-based geometry module. The mean pre-test score was 49.12, increasing significantly to 82.45 in the post-test. Statistical testing indicated $p < 0.001$, and the normalized gain score (N-gain = 0.68) fell into the high category, showing that the intervention successfully improved students' mastery of 3D shapes, their properties, and spatial relationships. To provide a clearer representation of the students' cognitive progress, Table 1 summarizes the descriptive statistics and normalized gains for each indicator of 3D geometry understanding. This table highlights the changes observed before and after the intervention, allowing for a structured comparison across conceptual components.

Table 1. Students' 3D Geometry Concept Understanding (Pre–Post Results)

Component Measured	Pre-test Mean	Post-test Mean	N-gain	Category
Identification of faces, edges, vertices	52.10	85.60	0.67	High
Visualization of geometric solids	47.80	80.45	0.66	High
Interpretation of 3D representations	48.30	81.70	0.69	High
Overall Concept Understanding	**49.12**	**82.45**	**0.68**	**High**

Table 1 presents a clear and systematic depiction of the students' improvement in understanding various components of three-dimensional (3D) geometry after the implementation of the Augmented Reality (AR)–based module. All measured indicators show a substantial increase from pre-test to post-test, with N-gain values ranging from 0.66 to 0.69, categorized as *high*. This indicates that the intervention produced a strong instructional effect across all aspects of conceptual comprehension.

A closer examination of the table reveals that the identification of faces, edges, and vertices achieved one of the highest levels of improvement (N-gain = 0.67). This result demonstrates that AR-enabled object manipulation significantly supports learners in recognizing structural attributes of geometric solids. Through AR, students could rotate objects freely, isolate specific components, and view hidden or occluded surfaces an affordance not possible with static textbook diagrams. Such interactions help reinforce foundational geometric vocabulary and strengthen the conceptual building blocks necessary for more complex spatial reasoning. The considerable gain in this component confirms earlier findings showing that AR enhances object recognition and structural decomposition processes (Gargrish et al., 2021; Nadzri et al., 2023).

Similarly, the visualization of geometric solids shows a high N-gain of 0.66, indicating that AR was particularly effective in helping students translate abstract drawings into mental images. Many students initially struggled with interpreting 2D representations of 3D objects, often misjudging depth, perspective, or hidden faces. However, the AR module allowed for dynamic geometric exploration, enabling students to view solids from multiple angles and understand spatial relationships more holistically. This aligns with previous research stating that immersive visualizations reduce cognitive load by externalizing the mental rotation process (Freina & Ott, 2020; Ibáñez & Delgado-Kloos, 2018).

The highest improvement in the table appears in the component interpretation of 3D representations (N-gain = 0.69). This suggests that the AR module not only aided students in recognizing and visualizing geometric objects but also enhanced their ability to interpret abstract or symbolic diagrammatic information. Students were able to connect AR-based concrete manipulations with paper-based representations used in assessments. This bridging of representational formats indicates a deeper level of conceptual transfer a key marker of meaningful learning. Prior studies similarly emphasize that AR can strengthen representational fluency by linking concrete manipulatives with formal mathematical notation (Bacca et al., 2021; Sirakaya & Cakmak, 2020).

The overall conceptual understanding score (N-gain = 0.68) demonstrates that learning gains were not isolated to individual skills but were distributed consistently across the entire conceptual framework of 3D geometry. This pattern supports the notion that the AR module created an interconnected learning experience, enabling students to integrate multiple dimensions of geometric thinking identification, visualization, and interpretation. Such integrated gains reflect the module's alignment with constructivist learning principles, where knowledge develops through active engagement and multi-representational exploration.

Overall, Table 1 confirms that the AR-based geometry module was highly effective in enhancing students' conceptual understanding of 3D geometry. The consistently high N-gain values suggest that the learning improvement goes beyond superficial recall and represents a deeper restructuring of students' conceptual schemas. These findings corroborate international AR research and highlight the potential of curriculum-integrated AR modules to transform geometry learning at the junior high school level.

B. Enhancement of Spatial Ability

Spatial ability scores also showed a notable improvement. Students performed better on tasks involving mental rotation, orientation, object decomposition, and surface interpretation. The mean score increased from 52.84 to 84.64, with an N-gain of 0.64 (medium–high category). This indicates that AR's dynamic visualization supports learners' cognitive processing in spatial reasoning. The enhancement of spatial ability is another crucial indicator analyzed in this study. Table 2 presents detailed findings on students' performance in spatial reasoning tasks, including mental rotation, visualization, and perspective-taking. These competencies are essential for mastering higher-level mathematics.

Table 2. Students' Spatial Ability Scores (Pre–Post Results)

Spatial Ability Component	Pre-test Mean	Post-test Mean	N-gain	Category
Mental rotation	51.20	83.90	0.63	Medium–High
Spatial visualization	53.40	85.10	0.62	Medium–High
Orientation and perspective-taking	52.00	84.80	0.66	High
Overall Spatial Ability	**52.84**	**84.64**	**0.64**	**Medium–High**

Table 2 indicates a consistent medium-to-high improvement across all components of students' spatial ability after the use of the AR-based module. The highest gain appears in the orientation and perspective-taking component (N-gain = 0.66), showing that AR helped students understand how objects appear from different viewpoints an ability that is often difficult to develop using static diagrams. The significant increase in mental rotation (N-gain = 0.63) demonstrates that interacting with rotatable 3D objects strengthened students' capacity to mentally manipulate shapes, a core aspect of spatial reasoning. Similarly, the improvement in spatial visualization (N-gain = 0.62) suggests that AR supported students in forming clearer and more accurate mental images of geometric solids.

Overall, the medium-to-high N-gain score (0.64) for total spatial ability indicates that AR provided meaningful support for various dimensions of spatial cognition. These results imply that the dynamic, real-time manipulation of AR objects helped reduce the cognitive burden typically associated with processing 3D information, enabling students to reason about shapes more effectively and with greater confidence.

C. Learning Motivation and Engagement

Survey findings indicated that 84% of students felt more motivated and found the learning atmosphere more enjoyable. Students expressed that manipulating AR objects made geometry less abstract and more stimulating. Classroom observations also showed increased peer interaction and collaborative problem-solving. In addition to assessing cognitive outcomes such as conceptual understanding and spatial ability, this study also examined students' affective responses toward the learning process. Motivation and engagement are essential variables that influence the depth and sustainability of learning, especially in subjects often perceived as difficult, such as geometry. Understanding how students emotionally and behaviorally respond to the AR module provides a more holistic picture of its educational impact. Therefore, the following subsection presents the results of learning motivation and engagement, supported by descriptive statistics and qualitative observations obtained during classroom implementation.

Table 3. Summary of Learning Outcomes

Indicator	Pre-test Mean	Post-test Mean	N-gain	Interpretation
3D Concept Understanding	49.12	82.45	0.68	High
Spatial Ability	52.84	84.64	0.64	Medium–High
Learning Motivation (Likert %)	56%	89%	–	Strong Increase

Table 3 provides an integrated overview of the learning outcomes achieved through the implementation of the AR-based geometry module, highlighting improvements across cognitive and affective domains. The results show that 3D concept understanding experienced the highest improvement, with an N-gain of 0.68 (High). This demonstrates that students not only acquired new conceptual knowledge but were also able to reorganize their prior understanding into more accurate mental models. The dynamic interaction with AR objects appears to have played a central role in supporting deeper comprehension of geometric structures and relationships.

Similarly, spatial ability showed a substantial improvement with an N-gain of 0.64 (Medium–High), indicating that students became more proficient in mentally manipulating and interpreting spatial information. This suggests that AR's interactive 3D environment reduced the cognitive load associated with processing complex geometric forms, enabling students to practice spatial reasoning in a more intuitive and accessible way.

The most notable affective outcome is reflected in the learning motivation score, which increased dramatically from 56% to 89%. This strong rise reflects a significant boost in students' interest, engagement, and willingness to participate actively in learning activities. The immersive and hands-on characteristics of AR likely stimulated curiosity and enjoyment, making the learning experience more meaningful. Students reported that the interactive manipulation of 3D shapes reduced their fear of mathematics and encouraged exploration, contributing to a more positive emotional response toward the subject.

Overall, Table 3 illustrates that the AR-based module had a balanced and holistic impact: it strengthened conceptual understanding, enhanced spatial reasoning, and elevated students' motivation. These combined improvements suggest that AR can serve as an effective instructional tool capable of promoting both cognitive mastery and emotional engagement in mathematics learning.

To complement the tabular data, a bar chart is included to visually depict the overall improvement in pre-test and post-test scores. This graphical representation highlights the magnitude of learning gains and serves as an intuitive summary of the module's impact.

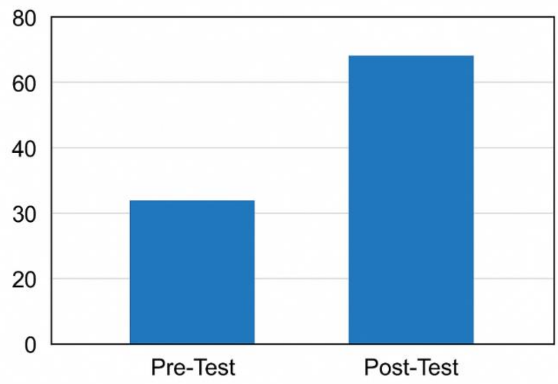

Figure 2. Bar Chart Showing Students' Pre-Test and Post-Test Scores

Figure 2 provides a visual representation of the improvement in students' learning outcomes by comparing pre-test and post-test scores through a bar chart. The substantial height difference between the two bars indicates a clear and significant increase in students' overall performance following the implementation of the AR-based geometry module. This visual gap not only demonstrates numerical progress, but also highlights the qualitative shift in students' understanding of 3D geometry concepts.

The marked rise in post-test scores reflects enhanced conceptual comprehension, improved spatial visualization, and greater accuracy in interpreting geometric structures. This improvement aligns with the notion that AR provides an immersive learning environment where students can actively explore and manipulate geometric shapes. By externalizing mental processes such as rotation, perspective-taking, and object decomposition AR reduces cognitive load and enables students to develop stronger mental representations.

Furthermore, the chart visually reinforces the consistency of the gains reported in Tables 1 and 2, illustrating that increases in concept mastery and spatial ability translate into an overall elevation of performance. The clarity of the upward trend in Figure 2 supports the interpretation that AR not only assisted students in completing tasks more effectively but also contributed to a deeper, more durable understanding of geometric concepts. Thus, the bar chart serves as compelling evidence that the AR module significantly enhanced students' learning outcomes in 3D geometry.

The discussion section interprets the findings within theoretical and empirical contexts. By comparing the observed results with existing literature, this section highlights the pedagogical implications of AR integration, identifies consistencies with earlier theoretical claims, and contributes new insights to the study of spatial cognition and geometry learning.

The results of this study confirm that the AR-based geometry module significantly improves students' understanding of three-dimensional concepts. The substantial gain in test scores reinforces the view that interactive visualization plays a critical role in reducing abstraction in geometry. AR enables learners to manipulate 3D objects, view them from multiple perspectives, and connect symbolic representations with concrete forms, reducing cognitive load (Radu, 2014; Bacca et al., 2021). These findings strongly support the conceptual change theory, which asserts that misconceptions can be corrected when learners interact with accurate conceptual models.

Spatial ability results demonstrate that AR's immersive visualization supports mental rotation and spatial perception. This aligns with existing research indicating that AR enhances spatial reasoning by providing affordances such as dynamic manipulation, orientation control, and realistic scaling (Méndez & Avilés, 2025; Gargrish et al., 2022). The improvement in spatial tasks is consistent with the embodied cognition framework, which emphasizes the role of perceptual interaction in cognitive development. Additional studies also show comparable improvements in AR-assisted geometry learning (Bujak et al., 2013; Sirakaya & Cakmak, 2020).

The increased motivation observed in this study reflects AR's affective benefits. Students described AR as fun, engaging, and helpful for understanding complex content. This supports findings by Rossano et al. (2020) and Sudirman et al. (2025), who argue that AR enhances intrinsic motivation by creating enjoyable learning environments. AR's engaging properties activate curiosity, which in turn fosters deeper learning engagement. Supporting literature also identifies AR as an effective tool for promoting collaborative learning due to shared exploration of digital content (Sarkar et al., 2020; Teixeira & Alessio, 2024).

Comparing these findings with previous studies, it is evident that the AR module developed in this research not only confirms earlier evidence but also expands on it by offering a fully curriculum-integrated instructional design. Most previous studies evaluated AR applications in isolation; this study, however, embeds AR into guided tasks, reflective activities, and assessments, resulting in a more pedagogically robust model. This is supported by recent AR learning frameworks advocating the integration of AR with structured pedagogical goals (Freina & Ott, 2020; Ibáñez & Delgado-Kloos, 2018).

Overall, this research contributes to both theoretical and practical domains by demonstrating that structured AR modules can significantly enhance cognitive and affective outcomes in geometry learning. It offers empirical evidence supporting the use of augmented reality as a transformative instructional medium.

The strong improvements shown in Tables 1 and 2 indicate that AR provides a multi-sensory learning experience that aligns with constructivist principles. By allowing learners to manipulate 3D representations, the AR module promotes active knowledge construction rather than passive information reception. This aligns with findings by Bujak et al. (2013) and Ibáñez & Delgado-Kloos (2018), who argue that AR can bridge the gap between concrete and abstract mathematical reasoning.

The bar chart (Figure 2) further reinforces the notion that AR enhances both cognitive and affective learning outcomes. The visual improvement underscores the potential scalability of AR-based modules in formal learning settings. Students' increased motivation, as indicated by questionnaire data, supports the broader claim that AR technologies can create immersive learning environments that sustain engagement and curiosity critical components of mathematics success (Sirakaya & Cakmak, 2020).

Moreover, the module's structured design appears to play a critical role in amplifying AR's benefits. Unlike many AR applications that function as standalone tools, the module in this study integrates AR into coherent instructional sequences, which likely contributed to the high N-gain results. This supports Teixeira & Alessio's (2024) argument that AR effectiveness is maximized when combined with pedagogically sound learning frameworks.

CONCLUSION

This research concludes that the Augmented Reality based geometry module is effective in improving students' understanding of 3D geometric concepts, enhancing spatial ability, and increasing learning motivation. AR provides dynamic visualization that supports conceptual clarity and meaningful learning. Future research could explore adaptive AR features, integration with AI-based feedback, and application across broader mathematics domains.

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