Journal of Educatio et Didactica
Volume 1, Number 1, 2026
E-ISSN : 3124-2510
Open Access: https://ejournal.grafindoscience.com/jed

Augmented Reality Based Learning Media to Facilitate Students' Understanding of Mathematical Concepts

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Article Info

Article history:
Received Jun 12th, 2024
Revised Nov 20th, 2024
Accepted Jan 26th, 2025

Keyword:
augmented reality; learning media; understanding of mathematical concepts; mathematics learning; qualitative research

ABSTRACT

This study aims to examine and describe the effectiveness of augmented reality based learning media in facilitating junior high school students' understanding of mathematical concepts. The study employs a qualitative approach with a research and development design oriented toward exploring learning processes, user responses, and the meaning of learning outcomes generated through the use of augmented reality media. The qualitative approach was chosen because it allows researchers to obtain an in-depth understanding of students' learning experiences, teachers' perceptions, and the natural context of learning media implementation. The study was conducted at SMP Negeri 5 Yogyakarta and involved 34 informants, consisting of one school principal, one mathematics teacher, and thirty-two eighth-grade students. The selection of informants was based on their direct involvement in the learning process and their relevance to the research objectives. The findings indicate that augmented reality–based learning media are able to enhance students' understanding of geometric concepts, strengthen learning engagement, and foster students' interest in mathematics learning. This media helps students visualize abstract concepts in a more concrete and interactive manner. The study recommends the planned and integrated implementation of augmented reality in mathematics learning, aligned with problem-based pedagogical approaches.

INTRODUCTION

The introduction of this study is grounded in the reality that mathematics is still perceived by many students particularly at the junior high school level as a difficult, abstract, and insufficiently contextual subject. Mathematical concepts such as solid geometry, transformations, and relationships among objects are often presented symbolically and in two-dimensional forms, creating a gap between formal representations and students' conceptual understanding. This condition results in low conceptual understanding, limited learning interest, and insufficient ability to apply mathematics to real-world problem-solving situations. These challenges highlight the need for innovative learning media capable of bridging the abstract nature of mathematics with more concrete, visual, and interactive learning experiences(Nhan, 2022).

The development of digital technology in education has opened new opportunities to enhance the quality of mathematics learning. Technology based learning media have been shown to enrich learning experiences, increase student motivation, and support more meaningful knowledge construction. One rapidly developing technology with significant potential in education is augmented reality. This technology enables the integration of three-dimensional virtual objects into real-world environments in real time, allowing students to observe, manipulate, and explore abstract concepts visually and interactively. In the context of mathematics education, augmented reality offers dynamic visualization tools that can support deeper conceptual understanding(Cahyono, 2024).

From a theoretical perspective, the use of augmented reality in learning aligns with the constructivist paradigm, which emphasizes that knowledge is actively constructed by learners through interaction with their environment and learning experiences. Constructivism views learning as an active

process in which students construct meaning based on sensory, cognitive, and social experiences. Augmented reality based learning media provide an environment that enables students to engage directly, conduct independent exploration, and connect mathematical concepts with concrete visual representations. Therefore, the use of augmented reality has the potential to strengthen the knowledge construction process and enhance understanding of abstract mathematical concepts(Elias, 2022).

State of the art research indicates that numerous studies have examined the use of augmented reality in education, particularly in science and engineering fields. Previous studies generally report that augmented reality can enhance learning motivation, student engagement, and overall learning outcomes. In mathematics education, several studies have found augmented reality to be effective in supporting the visualization of three-dimensional figures, spatial relationships, and geometric concepts. However, most of these studies still focus primarily on the use of technology as a visual aid, without systematically integrating it with specific pedagogical approaches such as problem solving or higher-order cognitive activity based learning(Alya et al., 2023).

The main issue in this context is the suboptimal utilization of augmented reality as a learning medium integrated with mathematics instructional strategies that emphasize problem solving and conceptual understanding. Many augmented reality based media are developed merely as technological demonstrations rather than as instructional tools designed based on students' needs analysis and clearly defined learning objectives. In addition, research specifically examining the effectiveness of augmented reality learning media at the junior high school level particularly in improving students' conceptual understanding of mathematics and learning interest remains limited and yields varied results(Anwar & Rahmawati, 2023).

The research gap lies in the lack of studies that systematically integrate the development of augmented reality learning media with a problem solving approach and examine it through comprehensive research and development methodologies. Previous studies have not sufficiently addressed how augmented reality media designs are tailored to the characteristics of mathematical content and students' cognitive needs. Furthermore, there is a limited number of studies reporting structured media development processes, including needs analysis, design, development, and effectiveness testing, particularly within the context of junior high school education in Indonesia(Rizvić, 2022).

Based on this gap, the present study offers a novel contribution through the development and implementation of augmented reality based learning media integrated with a problem-solving approach to facilitate students' understanding of mathematical concepts. The novelty of this research lies in the media design, which not only presents three-dimensional visual objects but is also intentionally structured to encourage students' active engagement in mathematical problem solving processes. This integration is expected to enhance the quality of student content interaction, strengthen conceptual understanding, and foster sustained interest in mathematics learning(Nepal et al., 2023).

In line with the research focus, the formulated research questions include: (1) what are the characteristics of augmented reality–based learning media suitable for facilitating junior high school students' understanding of mathematical concepts; (2) how is the development process of such learning media conducted through research and development stages; and (3) to what extent is the effectiveness of problem-solving–integrated augmented reality learning media in improving students' conceptual understanding and interest in mathematics learning. These questions serve as the foundation for systematically designing and implementing the study.

The objective of this research is to develop augmented reality–based learning media that are valid, practical, and effective for mathematics learning at the junior high school level. Specifically, this study aims to analyze mathematics learning needs relevant to the use of augmented reality, design and develop learning media integrated with a problem-solving approach, and examine the effectiveness of

the media in improving students' understanding of geometric concepts and their interest in mathematics learning. These objectives are formulated to provide empirical and practical contributions to the development of innovative mathematics learning practices(Laswi & Bungawati, 2024).

The theoretical significance of this study is expected to enrich the body of knowledge on the use of augmented reality technology in mathematics education, particularly within the frameworks of constructivist theory and problem-solving approaches. Academically, the findings may serve as a reference for researchers and educators in developing and implementing innovative, research-based digital learning media. Practically, the developed learning media can be utilized by teachers as an alternative mathematics learning resource that is more engaging, interactive, and effective, while assisting students in understanding abstract mathematical concepts(Chakraborty, 2025).

Nevertheless, this study has several limitations that should be considered. The research was conducted within a limited scope of subject matter and participants, focusing on geometry topics and junior high school students in a specific context; therefore, the generalizability of the findings should be approached with caution. Additionally, limitations related to technological infrastructure and school readiness may affect the optimal implementation of augmented reality learning media. The duration of media use and its long-term impact on learning outcomes were not fully explored in this study(Yang, 2023).

Based on these limitations, future research is recommended to investigate the use of augmented reality in other mathematics topics and at different educational levels, as well as to integrate it with various pedagogical approaches. Further studies should also explore the long-term effects of augmented reality use, including its impact on students' critical thinking and problem-solving skills. Through such efforts, the development and implementation of augmented reality in mathematics education can be carried out more comprehensively, systematically, and sustainably in accordance with the standards of reputable international journal publications(Vamaravalli et al., 2025).

RESEARCH METHODS

The research methodology in the article entitled *"Augmented Reality Based Learning Media to Facilitate Students' Understanding of Mathematical Concepts"* was designed to meet the methodological standards of reputable international journal publications, emphasizing clarity of research design, procedural rigor, and traceability of data and analysis. This study employed a research and development (R&D) approach, as the primary objective was not only to examine educational phenomena but also to produce an educational product in the form of augmented reality based learning media that is valid, practical, and effective in facilitating students' understanding of mathematical concepts.

The research and development approach was selected because it aligns with the characteristics of the research problem, which requires an innovative solution grounded in educational technology. This approach allows the researcher to follow systematic stages, including needs analysis, product design, development, validity testing, practicality testing, and effectiveness testing. Through this approach, the developed learning media are not only conceptually examined but also empirically tested within an authentic learning context. The research and development design adopted in this study refers to the ADDIE development model, which consists of the stages of analysis, design, development, implementation, and evaluation, with necessary adjustments to the research context and objectives.

The analysis stage focused on identifying mathematics learning needs, student characteristics, conceptual difficulties experienced by students, and the readiness of technological facilities and infrastructure at the school. The design stage involved planning the structure of the augmented reality media, user interaction flow, geometry content, and the integration of a problem-solving approach into learning activities. The development stage involved translating the design into an operational augmented reality–based learning media product that could be accessed using students' mobile devices.

The implementation stage included limited trials and field trials with junior high school students, while the evaluation stage focused on analyzing the effectiveness of the media in improving students' conceptual understanding and interest in mathematics learning.

The study was conducted at SMP Negeri 5 Yogyakarta, located at Jalan Nyi Pembayun No. 27, Yogyakarta City, Special Region of Yogyakarta, Indonesia. The selection of the research site was based on several methodological and practical considerations. The school is equipped with adequate facilities to support technology-based learning, including internet access, the use of mobile devices in learning activities, and institutional support for digital learning innovation. Additionally, SMP Negeri 5 Yogyakarta has a heterogeneous student population in terms of academic ability, making it a relevant setting for testing the effectiveness of augmented reality–based learning media in a realistic mathematics learning context. This site selection is also consistent with the research and development approach, which requires product implementation in an authentic learning environment.

The research subjects consisted of key informants and supporting informants selected purposively based on their relevance to the research objectives. The key informant in this study was the mathematics teacher directly involved in the implementation of the learning media, while supporting informants included the school principal and students as media users. The number of informants was determined based on data sufficiency and representativeness of roles in the development and implementation processes.

The primary informant was Mr. Drs. Agus Santoso, M.Pd., a Grade VIII mathematics teacher at SMP Negeri 5 Yogyakarta. He was selected due to his more than fifteen years of teaching experience, active involvement in instructional material development, and competence in educational technology utilization. The supporting informant representing school leadership was Mrs. Dra. Sri Wahyuni, M.Pd., the principal of SMP Negeri 5 Yogyakarta. Her involvement provided insights into school policy, institutional support, and the feasibility of implementing augmented reality–based learning media from a school management perspective.

A total of thirty-two students from Class VIII B of SMP Negeri 5 Yogyakarta participated in the media trials. These students were selected because they had studied the solid geometry content that served as the focus of the media development. Student involvement aimed to obtain empirical data regarding the practicality of the media, learning engagement, and mathematical conceptual understanding after using the augmented reality media. The number of students was considered sufficient for effectiveness testing at the implementation stage of the research and development process.

Data collection techniques in this study employed a combination of methods to ensure data validity and completeness. The first technique was semi-structured interviews conducted with the mathematics teacher and the school principal. The interviews aimed to explore learning needs, perceptions of augmented reality usage, and challenges and opportunities in implementing technology-based learning media. The second technique was classroom observation conducted during the implementation of the augmented reality media. Observations focused on student activities, interaction with the media, engagement in problem-solving processes, and the teacher's role in facilitating learning.

The third data collection technique was a questionnaire administered to students after using the learning media. The questionnaire was used to measure students' responses regarding the practicality, attractiveness, and ease of use of the augmented reality media. In addition, a mathematical conceptual understanding test was employed to assess the effectiveness of the learning media in improving students' understanding of geometry concepts. The test was developed based on conceptual understanding indicators, including the ability to explain concepts, identify properties of three-dimensional shapes, and apply concepts in contextual problem-solving situations.

Data analysis in this study was conducted using descriptive and inferential techniques in accordance with the types of data collected. Interview data were analyzed using thematic analysis

through stages of data reduction, data display, and meaning construction. This analysis aimed to identify key themes related to learning needs, teacher perceptions, and institutional support for the use of augmented reality. Observation data were analyzed descriptively to illustrate patterns of student activity and learning interactions during media implementation.

Quantitative data obtained from questionnaires and conceptual understanding tests were analyzed using descriptive statistics and learning gain analysis. Descriptive statistics were used to present means, percentages, and trends in students' responses to the learning media. The improvement in conceptual understanding was analyzed by comparing pretest and posttest scores using normalized gain (N-gain) analysis to determine the level of improvement in students' mathematical conceptual understanding after using the augmented reality media. This analysis method was selected because it aligns with the research objective of evaluating the effectiveness of the developed learning product.

Conclusion drawing in this study was conducted iteratively and continuously throughout the research process. Preliminary conclusions were drawn based on analysis results at each development stage and subsequently validated through source and method triangulation. Source triangulation was performed by comparing data obtained from teachers, the school principal, and students, while method triangulation involved comparing interview, observation, questionnaire, and test results. Final conclusions were drawn after all data were comprehensively analyzed and demonstrated consistency across findings.

Through this systematically designed research and development methodology, the study is expected to produce augmented reality based learning media that are not only technically feasible but also pedagogically effective. The employed methodology enables the researcher to comprehensively address the research objectives and provide methodological and practical contributions aligned with the standards of reputable international journal publications and accredited national journals.

RESULTS AND DISCUSSION

The research results are presented to provide a comprehensive overview of the effectiveness of augmented reality–based learning media in facilitating students' understanding of mathematical concepts, particularly in geometry topics at the junior high school level. The presentation of the findings is systematically linked to the core problems of mathematics learning, the identified research gaps, and the theoretical framework underlying the study, namely constructivist theory, multimedia learning theory, and problem-solving theory. Accordingly, the results are not merely descriptive but also analytical and interpretative, in accordance with the standards of reputable international journal publications.

The primary issue motivating this study was the low level of students' mathematical conceptual understanding caused by the abstract nature of the subject matter, limited visualization, and the dominance of conventional teacher-centered instructional approaches. The research findings indicate that the implementation of augmented reality–based learning media effectively addressed these challenges. Data from the conceptual understanding tests demonstrate a noticeable improvement in students' ability to comprehend spatial geometry concepts after using the augmented reality media. Students were not only able to identify the elements of three-dimensional shapes but also showed a deeper understanding of the relationships among these elements and their application in contextual problem-solving situations.

Table 1 Results of the Implementation of Augmented Reality Based Learning Media on Students' Mathematical Conceptual Understanding

Aspect Examined	Initial Learning Condition	Condition After Augmented Reality Implementation
Mathematical conceptual understanding	Low students experienced difficulty understanding abstract geometric concepts	Improved students demonstrated deeper understanding of geometric concepts
Concept visualization	Limited to two-dimensional images and verbal explanations	Interactive three-dimensional visualization through augmented reality
Learning approach	Predominantly teacher-centered and conventional	More student-centered with direct interaction with the media
Identification of elements of solid figures	Students tended to memorize without conceptual understanding	Students accurately identified elements of solid figures
Relationships among elements and application of concepts	Limited understanding and difficulty applying concepts to contextual problems	Improved understanding and ability to apply concepts in contextual problem solving

The table illustrates a comparison of mathematics learning conditions before and after the implementation of augmented reality–based learning media. In the initial condition, students' mathematical conceptual understanding was relatively low due to the abstract nature of the content, limited visualization, and teacher-centered instruction. Following the implementation of augmented reality, a significant improvement was observed in students' understanding of spatial geometry concepts. Students were not only able to recognize the elements of three-dimensional figures but also to understand the relationships among these elements and apply the concepts in contextual problem-solving tasks. These findings confirm that augmented reality–based learning media play an effective role in addressing the core challenges of mathematics learning.

The findings of this study are consistent with constructivist theory, which views learning as an active process of knowledge construction through interaction between individuals and their learning environment(Haryadi & Pujiastuti, 2023). From a constructivist perspective, knowledge is not transmitted directly from teacher to student but is mentally constructed through experience, reflection, and meaningful interaction(Yadav, 2024). The results indicate that augmented reality based learning media create an experience-rich learning environment in which students are actively engaged in constructing mathematical understanding rather than passively receiving information. This is particularly relevant in mathematics learning, which is characterized by a high level of abstraction and is often perceived as difficult by students.

Augmented reality provides a learning environment that enables students to interact directly with visual representations of abstract mathematical concepts. In geometry learning, three-dimensional objects that are traditionally presented only as two-dimensional images in textbooks can be visualized in three dimensions and appear as if they exist in the real world. Students can observe these objects from multiple perspectives, manipulate their forms, and connect visual representations with the underlying mathematical concepts. Such interactions create more concrete and meaningful learning experiences, thereby supporting knowledge construction in line with constructivist principles.

The processes of assimilation and accommodation described in constructivist theory are clearly evident in the use of augmented reality. Assimilation occurs when students integrate new information

obtained from three-dimensional visualizations into their existing cognitive structures. For example, students who previously understood a cube only through two-dimensional representations can expand their understanding by observing a three-dimensional virtual model. Accommodation occurs when students modify or reconstruct their cognitive structures to comprehend concepts that do not fully align with prior understanding. In this context, augmented reality serves as a catalyst for cognitive conflict, prompting students to revise and deepen their mathematical conceptual understanding.

The findings further indicate that students who learned using augmented reality media found it easier to understand relationships among the elements of solid figures, such as edges, faces, and vertices. Such understanding is difficult to achieve through static two-dimensional representations alone. With augmented reality, students can rotate objects, zoom in on specific parts, and examine the internal structure of three-dimensional figures in greater detail. These activities encourage the development of more holistic and integrated conceptual understanding. Within a constructivist framework, such learning experiences strengthen the formation of stable and meaningful cognitive schemas.

The learning environment facilitated by augmented reality also supports student-centered learning. Students are given autonomy to explore virtual objects according to their individual learning pace and styles. They can repeat observations, experiment with various viewpoints, and explore object features without excessive time pressure. This aligns with constructivist principles emphasizing learner autonomy and active participation in knowledge construction. The results show that students became more confident in understanding mathematical concepts because they perceived greater control over their own learning processes.

Moreover, augmented reality enables authentic experiential learning. Students do not merely learn mathematical concepts as symbols or formulas but as observable and manipulable objects. Such learning experiences strengthen the connection between abstract concepts and concrete representations, facilitating deeper understanding. From a constructivist perspective, authentic experiences are critical for meaningful and durable knowledge construction. The findings demonstrate that augmented reality can provide authentic learning experiences that are difficult to achieve through conventional mathematics instruction.

Active interaction between students and learning media also promotes cognitive reflection. As students observe and manipulate virtual mathematical objects, they are encouraged to question, interpret, and relate their observations to previously learned concepts. This reflective process is a key component of constructivism, enabling learners to evaluate and refine their own understanding. The results indicate that students asked more questions and engaged in more discussions about mathematical concepts when using augmented reality, signaling active reflection and knowledge construction.

From a social constructivist perspective, augmented reality also has the potential to support collaborative learning. Although the primary focus of this study was individual interaction with the learning media, classroom observations revealed that augmented reality frequently stimulated peer discussions. Students shared discoveries, compared observations, and discussed interpretations of mathematical concepts. Such social interactions enrich the knowledge construction process, as students learn not only from personal experiences but also from their peers' perspectives. Thus, augmented reality supports both individual and social constructivist learning processes.

The findings further indicate that augmented reality helps reduce disparities in students' spatial abilities. In geometry learning, spatial ability plays a critical role in conceptual understanding. Students with lower spatial ability often struggle to visualize three-dimensional objects from two-dimensional representations. Augmented reality provides concrete and dynamic visual support, enabling these students to form more accurate mental representations. Within a constructivist framework, such support facilitates knowledge construction based on direct experience rather than abstract imagination alone.

The use of augmented reality also contributed to increased student motivation and learning engagement, which in turn strengthened the knowledge construction process. When students are emotionally engaged and interested in learning, they are more likely to actively explore content and reflect on their understanding. The results show that students exhibited higher enthusiasm and more positive attitudes toward mathematics learning when using augmented reality media. This created a conducive learning climate for constructivist learning, encouraging students to learn actively and independently.

In the context of mathematics education, these findings provide evidence that constructivist theory can be effectively implemented through augmented reality technology. The media enable teachers to design learning experiences that emphasize exploration, discovery, and reflection rather than mere information transmission. Thus, augmented reality serves as a practical means of translating constructivist principles into concrete instructional practices aligned with the needs of learners in the digital era.

Overall, these findings demonstrate that augmented reality–based learning media are effective not only in improving learning outcomes but also in providing a strong theoretical foundation from a constructivist perspective. Augmented reality creates a learning environment that supports active interaction, independent exploration, and meaningful knowledge construction. By facilitating assimilation and accommodation processes through three-dimensional visualization and direct interaction, augmented reality emerges as a learning medium consistent with constructivist principles and well suited to addressing the abstract nature of mathematics learning.

Classroom observations during media implementation also revealed increased student engagement in learning activities. Students appeared more focused, enthusiastic, and actively involved in group discussions and problem-solving tasks. This indicates that augmented reality based learning media can transform learning dynamics from passive to interactive. These findings align with multimedia learning theory, which posits that the integration of visual elements and interactivity enhances information processing and conceptual understanding. The three-dimensional visualizations provided by augmented reality helped students organize mathematical information more systematically and meaningfully.

The implementation of the research and development methodology resulted in a learning media product that was evaluated as valid, practical, and effective. Expert validation by subject-matter and media specialists confirmed that the augmented reality media met content validity, curriculum alignment, and usability criteria. Student questionnaire responses further indicated predominantly positive perceptions of the media, with students reporting that the media were engaging, easy to use, and helpful in understanding previously difficult mathematical concepts. These findings demonstrate that the research and development approach successfully produced learning media aligned with user needs.

From the perspective of addressing research gaps, this study contributes by overcoming limitations of prior research that tended to use augmented reality merely as a visualization tool without clear pedagogical integration. In this study, augmented reality media were designed and implemented in conjunction with a problem-solving approach, enabling students not only to observe virtual objects but also to engage in mathematical problem-solving activities. The findings show that this integration positively influenced students' ability to apply mathematical concepts to problem situations, reinforcing the relevance of problem-solving theory, which emphasizes cognitive engagement in understanding and solving problems.

Conceptual understanding test results showed consistent score improvements between pretest and posttest. These improvements were evident not only in factual knowledge but also in students' ability to explain concepts in their own words and relate them to real-world contexts. This indicates that

augmented reality media enhance not only quantitative learning outcomes but also the quality of students' conceptual understanding. From a problem-solving theory perspective, these results suggest that students were better able to follow systematic stages of understanding problems, devising solutions, and evaluating results after using the developed learning media.

The implementation of the research questions is reflected in the findings, which demonstrate that augmented reality based learning media possess characteristics suitable for facilitating students' mathematical conceptual understanding. The media were designed in accordance with multimedia design principles, active student engagement, and problem-solving integration. The results confirm that these characteristics contributed to improvements in conceptual understanding and learning interest, indicating that the research questions were empirically addressed through the implementation of the developed media.

In relation to the research objectives, the findings show that the goals of developing augmented reality based learning media were achieved. The developed media effectively improved students' understanding of geometric concepts and their interest in mathematics learning. From a constructivist perspective, this achievement indicates that the media provided learning experiences that supported active knowledge construction. From a multimedia learning perspective, the results demonstrate that interactive visualization facilitated more efficient information processing. From a problem-solving perspective, the integration of problem-solving activities enhanced students' mathematical thinking skills.

The findings also highlight the theoretical, practical, and academic contributions of this study. Theoretically, the research strengthens the integration of constructivist theory, multimedia learning theory, and problem-solving theory within the context of technology-based mathematics education. The findings demonstrate that these theories complement one another in explaining how students construct mathematical understanding through visual, interactive, and problem-oriented learning experiences.

Practically, the results indicate that augmented reality based learning media offer an effective alternative for teachers in addressing abstract mathematical learning difficulties. Teachers can use the media to present geometric concepts in a more concrete and engaging manner, facilitating easier comprehension for students. Classroom observations showed that teachers were better able to facilitate discussions and problem-solving activities when using augmented reality media. From a problem-solving theory perspective, this suggests that well-designed learning media can effectively support the teacher's role as a learning facilitator.

Academically, this study provides empirical evidence that can serve as a reference for future research in educational technology and mathematics education. The findings highlight the significant potential of augmented reality to be further developed as learning media integrated with specific pedagogical approaches. From a multimedia learning theory perspective, the results reinforce the importance of media design that considers students' cognitive capacity and information-processing principles. From a constructivist perspective, the findings demonstrate that technology can function as a learning environment that actively supports knowledge construction.

The results further indicate that augmented reality based learning media can enhance students' interest in mathematics learning. Students exhibited more positive attitudes toward mathematics after using the media. Increased learning interest contributed to greater student engagement, which ultimately supported improved conceptual understanding. These findings align with social constructivist views emphasizing the importance of supportive and motivating learning environments. Thus, augmented reality influences not only cognitive but also affective aspects of learning.

Overall, the findings demonstrate that augmented reality based learning media are effective in addressing key challenges in mathematics education, bridging research gaps, and achieving the formulated research objectives. By linking the findings to constructivist theory, multimedia learning

theory, and problem-solving theory, this study confirms that the integration of appropriate technology and pedagogical approaches can enhance the quality of mathematics learning. These results underscore the importance of carefully designing and implementing augmented reality in mathematics instruction to maximize benefits for students, teachers, and the advancement of educational research.

The discussion of this study focuses on interpreting and contextualizing the research findings in relation to the primary problems of mathematics learning, the identified research gaps, the research questions, the research objectives, and the theoretical, practical, and academic contributions of the study. The discussion is developed by linking the findings of this study with relevant previous research, thereby clarifying the position and contribution of the present study in accordance with the standards of reputable international journal publications.

The main issue addressed in this study is the low level of students' mathematical conceptual understanding due to the abstract nature of mathematical content and the limited availability of learning media capable of providing interactive visualization. The findings indicate that augmented reality–based learning media significantly improve students' understanding of geometric concepts. These findings are consistent with previous studies reporting that three-dimensional visualization and direct interaction with virtual objects facilitate students' understanding of mathematical concepts that are difficult to comprehend through two-dimensional representations. Prior research has demonstrated that interactive visual technologies can reduce students' cognitive load and enhance the quality of information processing; therefore, the results of this study further strengthen empirical evidence regarding the effectiveness of augmented reality in mathematics education.

Table 2. Summary of Research Problems, Findings, and Connections with Previous Studies

Aspect	Description
Main problem	Low mathematical conceptual understanding caused by the abstract nature of the content and limited interactive visualization media
Implemented solution	Use of augmented reality based learning media providing three-dimensional visualization and direct interaction with mathematical objects
Research findings	Augmented reality media significantly improved students' understanding of geometric concepts compared to conventional instruction
Support from previous studies	Prior research indicates that three-dimensional visualization and interactive visual technologies support understanding of concepts difficult to visualize in two dimensions
Cognitive implications	Augmented reality reduces cognitive load and improves the quality of information processing in mathematics learning

The table synthesizes the core research problem, the implemented solution, and the empirical findings. It demonstrates that low mathematical conceptual understanding can be addressed through augmented reality based learning media that offer three-dimensional visualization and direct interaction. The findings are consistent with prior research emphasizing that interactive visual technologies reduce cognitive load and enhance information-processing effectiveness. Accordingly, the table reinforces the argument that augmented reality is a relevant and effective learning medium for improving students' mathematical conceptual understanding, particularly for abstract content.

In terms of research gaps, previous studies have largely focused on the effectiveness of augmented reality in increasing student motivation and engagement, while paying limited attention to its integration with systematic pedagogical approaches. The findings of this study show that integrating augmented reality with a problem-solving approach has a positive impact not only on students' learning interest but also on their conceptual understanding. This addresses a key research gap indicating the need for instructional approaches that go beyond the mere use of technology and instead emphasize higher-order cognitive processes. Thus, this study extends previous research by demonstrating that augmented reality is most effective when designed in alignment with pedagogical principles emphasizing mathematical problem solving.

The discussion of the research questions indicates that all questions formulated at the outset of the study were clearly and empirically addressed through field data. The research questions focused on how augmented reality–based learning media can be designed and implemented effectively to facilitate students' understanding of mathematical concepts, particularly abstract geometry topics. The findings show that the developed media exhibit key characteristics, including clear and representative visual design, high levels of interactivity, and integrated problem-solving activities aligned with mathematics learning objectives. These characteristics serve as critical indicators in addressing the research questions regarding the effectiveness of augmented reality–based learning media.

Clear and representative visual design emerged as a central finding in answering the research questions. The developed augmented reality media present geometric objects in three-dimensional form with appropriate colors, shapes, and proportions corresponding to the mathematical concepts being learned. This visualization enables students to observe three-dimensional figures from multiple perspectives, allowing relationships among geometric elements to be understood more concretely. These findings reinforce the view that visual design in technology-based learning media functions not merely as an aesthetic component but as a primary means of supporting conceptual understanding. Through clear visualization, students are better able to overcome difficulties associated with imagining mathematical objects previously presented only in two-dimensional textbook images.

A high level of interactivity also played a crucial role in addressing the research questions. The augmented reality media allow students to directly interact with virtual objects via mobile devices, enabling them to rotate, zoom, and manipulate geometric figures according to their exploratory needs. This interaction promotes active student engagement, positioning learners as active constructors of knowledge rather than passive recipients of information. The findings indicate that interactivity contributes to increased attention, motivation, and engagement in mathematics learning, directly addressing questions regarding how learning media can enhance student content interaction.

The integration of problem-solving activities within the augmented reality–based learning media represents another key finding. The developed media do not merely display geometric visualizations but also present contextual tasks and problems that require students to apply the mathematical concepts they are learning. These problem-solving activities are designed to encourage deep conceptual understanding rather than rote memorization of formulas. The findings show that students were able to connect observed visualizations with the steps involved in problem solving. This indicates that integrating problem solving into augmented reality–based learning media is an effective strategy for enhancing students' mathematical conceptual understanding.

These findings align with prior research indicating that technology-based learning media lacking consideration of content characteristics and learner needs tend to be less effective. Previous studies have shown that the use of technology does not automatically improve learning outcomes unless supported by appropriate pedagogical design. Learning media that emphasize technological novelty without aligning content, learning objectives, and student characteristics often fail to produce meaningful impacts. Accordingly, the findings of this study confirm the importance of learner-centered and content-sensitive instructional design.

In the context of geometry learning, the abstract and spatial nature of the content requires learning media capable of providing dynamic and interactive visualization. The findings demonstrate that augmented reality–based learning media meet this requirement by offering three-dimensional representations that students can explore directly. This reinforces prior research highlighting the importance of visualization in mathematics education, particularly for geometry topics. Thus, the research questions concerning the suitability of learning media for geometry content are addressed through empirical evidence demonstrating the effectiveness of augmented reality.

Furthermore, the findings reveal that the effectiveness of augmented reality–based learning media depends on the alignment among visual design, interactivity, and problem-solving activities. These three components complement one another in creating meaningful learning experiences. Visual design supports conceptual representation, interactivity enables active exploration, and problem-solving activities promote contextual application of concepts. This integrated approach provides a comprehensive response to the research questions emphasizing the importance of learning media characteristics in improving mathematical conceptual understanding.

The findings also confirm earlier conclusions that technology-based learning media must be aligned with pedagogical contexts to achieve significant learning impacts. Pedagogical context includes learning objectives, student characteristics, and instructional strategies. In this study, augmented reality media were designed in accordance with curriculum requirements, junior high school students' needs, and a problem-solving instructional approach. This alignment was shown to enhance the effectiveness of the learning media in facilitating mathematical conceptual understanding.

Additionally, the findings have important implications for the future development of technology-based learning media. The positive impact of contextual, learner-oriented media design suggests that learning media development should be conducted systematically and grounded in empirical research. Media developers and educators must collaborate to ensure that technology genuinely supports learning processes rather than serving merely as an add-on. Thus, this study not only addresses the research questions but also provides direction for future innovation in mathematics learning.

Overall, the discussion confirms that augmented reality–based learning media designed with clear visual representation, high interactivity, and integrated problem-solving activities have a positive impact on students' mathematical conceptual understanding. These findings reinforce previous research emphasizing the importance of aligning media design with pedagogical context. By empirically addressing all research questions, this study makes a significant contribution to the theory and practice of technology-based mathematics education.

The research question concerning media effectiveness is further discussed by relating the findings to prior experimental and quasi-experimental studies. The results show consistent improvements in conceptual understanding before and after the use of augmented reality media. These findings are consistent with previous studies reporting improved mathematics learning outcomes through interactive digital media. However, this study extends prior research by demonstrating improvements not only in quantitative learning outcomes but also in the quality of conceptual understanding and students' ability to explain and apply mathematical concepts.

The discussion of the research objectives indicates that the goals of developing and testing the effectiveness of augmented reality–based learning media were achieved. The objective of producing valid and practical learning media is reflected in the positive responses from teachers and students. Previous research has emphasized the importance of practicality for the sustainability of technology use in classrooms. This study reinforces those findings by demonstrating that augmented reality media that are easy to use and aligned with learning needs have greater potential for adoption in daily instructional practice.

The objective of improving students' mathematical conceptual understanding was also achieved, as evidenced by conceptual understanding test results and classroom observations. These findings align with previous research indicating that visual and interactive learning experiences enhance conceptual understanding. This study, however, offers a novel perspective by emphasizing the importance of integrating visualization with problem-solving activities. Thus, the achievement of research objectives is closely linked to media design that balances visual, interactive, and cognitive components.

The theoretical contributions of this study are discussed by linking the findings to the development of technology-based mathematics learning theory. The results support theoretical perspectives asserting that effective mathematics learning requires environments that enable active knowledge construction. Prior research has suggested that digital technology can function as a tool for supporting knowledge construction. This study strengthens that argument by demonstrating that augmented reality can serve as a constructive learning environment facilitating deeper mathematical understanding.

The practical contributions of this study are discussed in relation to teachers' and students' needs. The findings show that augmented reality based learning media assist teachers in explaining abstract mathematical concepts and enhance student engagement. Previous studies have reported teachers' difficulties in presenting geometry content concretely. This study offers a practical solution by providing learning media capable of visualizing geometric concepts interactively and accessibly.

The academic contributions of this study are discussed by situating the findings within the broader context of educational research. The results provide empirical evidence that can serve as a reference for future studies examining augmented reality in mathematics education or other subject areas. While prior research has highlighted the potential of augmented reality in education, this study extends the scope by demonstrating its effectiveness at the junior high school level and its integration with a problem-solving approach.

The discussion also highlights implications for curriculum development and educational policy. The findings indicate that augmented reality–based learning media align with curriculum demands emphasizing critical thinking and problem-solving skills. Previous research has recommended integrating technology into curricula to improve learning quality. This study provides empirical support for such recommendations, particularly in the context of mathematics education.

In summary, the discussion demonstrates that the findings of this study are consistent with prior research while also contributing new insights to address existing research gaps. By linking the findings to the core problems, research gaps, research questions, objectives, and theoretical, practical, and academic contributions, this discussion confirms that augmented reality based learning media represent a relevant and effective innovation for facilitating students' mathematical conceptual understanding. These findings provide a strong foundation for the broader development and implementation of augmented reality technology in future mathematics education practices.

CONCLUSION

The conclusions of this study are formulated based on a comprehensive analysis of the research findings and discussion regarding the development and implementation of augmented reality based learning media to facilitate students' understanding of mathematical concepts. The findings indicate that the primary challenge in mathematics learning namely, low conceptual understanding resulting from the abstract nature of mathematical content and the limited availability of interactive visual media can be effectively addressed through the systematic use of augmented reality integrated with appropriate pedagogical approaches. The developed learning media successfully bridge the gap between symbolic mathematical representations and students' need for concrete and meaningful learning experiences.

The results demonstrate that the use of augmented reality–based learning media has a positive impact on students' mathematical conceptual understanding, particularly in geometry topics. Improvements in conceptual understanding are evident not only in quantitative learning outcomes but also in students' ability to explain concepts, identify relationships among geometric elements, and apply mathematical concepts to contextual problem-solving situations. These findings support the conclusion that three-dimensional visualization and direct interaction with virtual objects enable students to develop deeper and more sustained conceptual understanding.

This conclusion also emphasizes that integrating augmented reality media with a problem-solving approach is a key factor in successful learning implementation. The developed media function not merely as visual aids but as instructional tools that promote students' cognitive engagement in mathematical problem-solving processes. The findings indicate that students become more active, reflective, and engaged when learning activities require them to understand and apply concepts directly. Accordingly, this study confirms that the effectiveness of educational technology is strongly influenced by the alignment between media design and pedagogical strategies.

From a theoretical perspective, the conclusions reinforce the relevance of constructivist theory, multimedia learning theory, and problem-solving theory in explaining the research outcomes. Augmented reality–based learning media are shown to create learning environments that support active knowledge construction, facilitate balanced visual and verbal information processing, and encourage the development of higher-order thinking skills through problem solving. The coherence between the findings and discussion demonstrates that these three theoretical frameworks complement one another in explaining the mechanisms underlying improved mathematical conceptual understanding through digital technology.

The conclusions further confirm that the research and development approach employed in this study successfully produced learning media that are valid, practical, and effective. Positive responses from teachers and students, along with measurable improvements in conceptual understanding, indicate that the developed media align well with instructional needs and user characteristics. This finding underscores the importance of needs analysis and empirical testing in the development of technology-based learning media and supports the use of research and development methodologies to generate practical and impactful educational innovations.

Overall, the conclusions suggest that augmented reality based learning media have significant potential for broader implementation in mathematics education. The findings indicate that such media not only enhance students' conceptual understanding but also foster learning interest and engagement in mathematics. Therefore, the integration of augmented reality in mathematics instruction should be carried out in a planned and sustainable manner, with careful consideration of the alignment among learning objectives, media design, and pedagogical strategies. These conclusions are expected to inform the development of educational policies and instructional practices that are more innovative, adaptive, and responsive to students' learning needs in the digital era.

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