JDIME : Journal of Development and Innovation In Mathematics Education

Volume 3, Number 1, April 2025, pp. 48-56
P-ISSN: 2986-2744 E-ISSN: 2986-402X
Open Access: http://dx.doi.org/10.32939/jdime.v3i1.5060

Development of Interactive Learning Media Based on Augmented Reality for Solid Geometry Concepts

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ARTICLE INFO

Article history:
Available online April 05, 2025

Kata Kunci:
Augmented Reality, Media Pembelajaran Interaktif, Bangun Ruang, Visualisasi Spasial, Teknologi Pendidikan

Keywords:
Augmented Reality, Interactive Learning Media, Solid Geometry, Spatial Visualization, Educational Technology

Abstrak

Penelitian ini bertujuan untuk mengembangkan media pembelajaran interaktif berbasis Augmented Reality (AR) pada materi bangun ruang sisi datar untuk siswa SMP. Media ini dirancang untuk meningkatkan pemahaman siswa terhadap konsep-konsep geometri, khususnya dalam hal visualisasi spasial. Penelitian ini menggunakan pendekatan pengembangan dengan model ADDIE (Analysis, Design, Development, Implementation, Evaluation). Proses pengembangan melibatkan validasi dari ahli materi dan media, serta uji coba pada siswa untuk mengevaluasi respon dan efektivitasnya. Hasil penelitian menunjukkan bahwa media pembelajaran AR yang dikembangkan sangat valid (94.5%) pada aspek kevalidan materi dan 91.3% pada desain media. Hasil angket respon siswa menunjukkan bahwa 93,7% siswa merasa media ini membantu mereka memahami konsep bangun ruang sisi datar secara lebih jelas, dan 89,1% siswa menyatakan bahwa media ini membuat pembelajaran matematika menjadi lebih menarik dan menyenangkan. Selain itu, Nilai rata-rata pretest adalah 61,7, sedangkan nilai rata-rata posttest meningkat menjadi 84,2. Hasil uji-t berpasangan menunjukkan nilai signifikansi sebesar p < 0,01, yang mengindikasikan bahwa peningkatan hasil belajar bersifat signifikan secara statistik. Media pembelajaran AR ini juga terbukti Valid dan efektif dapat membantu siswa dalam memvisualisasikan objek geometri yang kompleks, serta membuat proses belajar lebih menarik dan interaktif. Dengan demikian, penelitian ini menyarankan penggunaan AR sebagai alternatif pembelajaran yang efektif untuk meningkatkan pemahaman matematika di tingkat SMP.

Abstract

This study aims to develop an interactive learning medium based on Augmented Reality (AR) for teaching three-dimensional geometric shapes to junior high school students. The medium was designed to enhance students' understanding of geometric concepts, particularly in terms of spatial visualization. The research employed a development approach using the ADDIE model (Analysis, Design, Development, Implementation, Evaluation). The development process involved validation by content and media experts, as well as trials conducted with students to evaluate their responses and the medium's effectiveness. The results indicated that the developed AR learning medium was highly valid, with a material validity score of 94.5% and a media design validity score of 91.3%. Student response questionnaires revealed that 93.7% of students felt the medium helped them better understand the concepts of three-dimensional figures, while 89.1% stated that the medium made learning mathematics more engaging and enjoyable. Additionally, the average pretest score was 61.7, which increased to 84.2 in the posttest. A paired t-test showed a significance value of $p < 0.01$, indicating that the improvement in learning outcomes was statistically significant. The AR learning medium was thus proven to be valid and effective in assisting students in visualizing complex geometric objects, as well as making the learning process more engaging and interactive. Consequently, this study recommends the use of AR as an effective alternative learning tool to enhance students' mathematical understanding at the junior high school level.

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INTRODUCTION

Mathematics instruction at the primary and secondary levels often faces significant challenges, particularly concerning students' limited understanding of spatial concepts—especially within the topic of three-dimensional geometric solids. This subject demands strong spatial visualization and imagination skills for students to fully comprehend the three-dimensional representations of geometric objects. However, instructional practices remain predominantly reliant on conventional, text-based approaches and two-dimensional illustrations in printed textbooks, which inadequately convey the realistic properties and characteristics of spatial figures (Martyanti et al., 2022; Hidayat et al., 2023; Safitri & Yuliati, 2021; Maulina & Fauzi, 2020; Putra et al., 2022). Consequently, this inadequacy contributes to low student achievement in geometry and diminished interest and motivation in learning spatial mathematics.

With the advancement of digital technology in education, Augmented Reality (AR) has emerged as a promising and innovative solution to address the limitations of traditional learning media. AR enables the integration of three-dimensional virtual objects into the real environment in an interactive manner, thereby creating a more contextualized, immersive, and engaging learning experience for students (Ibáñez & Delgado-Kloos, 2018; Sirakaya & Cakmak, 2018; Zahra et al., 2020; Akçayır & Akçayır, 2017; Huang et al., 2021). In the context of teaching three-dimensional geometric solids, AR can be leveraged to present interactive 3D models of cubes, cuboids, pyramids, and prisms, enabling students to rotate, zoom in, and explore the structures from multiple perspectives.

Prior research has demonstrated that the use of AR-based learning media in mathematics significantly enhances students' conceptual understanding, spatial reasoning skills, and learning motivation (Köse et al., 2020; Lestari et al., 2021; Suh & Prophet, 2018; Chang et al., 2021; Alkhateeb et al., 2023). Moreover, AR aligns with constructivist learning approaches, wherein students actively construct knowledge through exploration and direct interaction with learning objects (Yilmaz et al., 2020; Phan & Choo, 2022; Sumarmo et al., 2019; Yuen et al., 2021; Wu et al., 2022). Therefore, the integration of AR technology into the development of mathematics learning media—specifically for solid geometry—is both relevant and necessary.

Despite the demonstrated potential of AR in mathematics education, a gap remains in the development of learning media specifically tailored to the characteristics of three-dimensional solid topics and aligned with the national curriculum. Furthermore, existing AR media often lack user-centered design principles, active learner engagement features, and systematic integration with assessment strategies (Susanti et al., 2023; Handayani et al., 2022; Setiawan et al., 2021; Rofiki et al., 2024; Andriyani & Nugroho, 2023). As such, there is a pressing need to develop interactive AR-based learning media that are not only technologically innovative but also pedagogically sound and responsive to students' learning needs and curricular demands.

This study offers a novel contribution by integrating Augmented Reality (AR) technology into an interactive learning medium designed specifically for the topic of three-dimensional geometric solids, using a contextual approach grounded in the Indonesian national curriculum. Unlike previous studies that employed more generic applications or presented only static 3D visualizations, the media developed in this research features dynamic interactivity, including object rotation, exploration of geometric components, automated annotations, and the integration of adaptive AR-based practice questions. These elements enable students to actively interact with and thoroughly comprehend geometric concepts (Lestari et al., 2021; Handayani et al., 2022; Alkhateeb et al., 2023; Susanti et al., 2023; Chang et al., 2021). Additionally, the research introduces another dimension of novelty by applying a design approach that combines pedagogical principles from constructivist learning theory and Cognitive Load Theory (CLT). This approach aims to reduce extraneous cognitive load while simultaneously promoting active engagement and deeper conceptual understanding. Previous studies have seldom integrated AR media design with cognitive load management principles and instructional design models that are appropriate for local educational contexts (Ibáñez & Delgado-Kloos, 2018; Akçayır & Akçayır, 2017; Sirakaya & Cakmak, 2018; Yilmaz et al., 2020; Wu et al., 2022).

Another notable novelty of this study lies in the use of open-source platforms, specifically Unity and Vuforia, which facilitate the development of multi-platform media that can be accessed across various devices such as Android smartphones and tablets. This technical approach addresses the urgent need for accessible digital learning media in diverse infrastructural conditions commonly found in Indonesian schools. Previous studies have yet to extensively explore this technical dimension, as many remain reliant on proprietary hardware or closed-system platforms (Setiawan et al., 2021; Zahra et al., 2020; Rofiki et al., 2024; Andriyani & Nugroho, 2023; Maulina & Fauzi, 2020). In addition to the technological features and pedagogical underpinnings, this research also offers novelty in its comprehensive validation process, which involves media experts, subject matter experts, and limited field trials with junior high school students to ensure practical applicability. This process yields empirical data regarding the media's effectiveness and user acceptability—critical aspects that are often overlooked in the development of AR-based instructional media (Suh & Prophet, 2018; Chang et al., 2021; Yuen et al., 2021; Huang et al., 2021; Phan & Choo, 2022).

Grounded in the aforementioned background, the aim of this study is to develop an interactive Augmented Reality-based learning media for teaching three-dimensional geometric solids. This media is intended to enhance students' engagement, spatial concept comprehension, and the overall effectiveness of the learning process. The development is conducted through a Research and Development (R&D) approach, incorporating expert validation, readability assessments, and limited user trials to evaluate both feasibility and the media's impact on student learning outcomes. This research aspires to make a meaningful contribution to the field of mathematics education through the innovation of technology-integrated learning tools and to serve as a reference for educators, media developers, and future researchers.

METHOD

This study adopts a Research and Development (R&D) approach, employing a modified version of the ADDIE model (Analysis, Design, Development, Implementation, and Evaluation), which has been widely recognized for its effectiveness in the development of technology-based instructional media (Branch, 2009; Molenda, 2015; Alqahtani & Mohammad, 2015; Setiawan et al., 2021; Rofiki et al., 2024). The ADDIE model was selected for its systematic yet flexible framework that supports continuous design and evaluation of learning media.

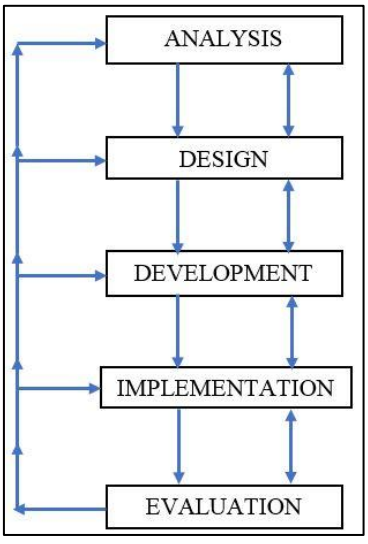

Figure 1. Research and Development (R&D) Model: ADDIE

The first stage, needs analysis, was conducted through classroom observations and interviews with junior high school teachers and students. This stage aimed to identify learning challenges related to three-dimensional geometric solids and to examine the characteristics of learners and their educational contexts. The findings from this phase served as the foundation for

designing content and media features aligned with students' needs and curriculum demands (Rahmawati et al., 2020; Lestari et al., 2021; Hidayat et al., 2023; Alkhateeb et al., 2023; Handayani et al., 2022).

In the design stage, the researchers developed the instructional flow, storyboard, user interface designs, and 3D object prototypes to be visualized through AR media. The design process was guided by instructional design principles rooted in constructivist theory and Cognitive Load Theory (CLT) to ensure that the media supports meaningful learning and avoids cognitive overload (Mayer, 2017; Paas & Sweller, 2014; Phan & Choo, 2022; Ibáñez & Delgado-Kloos, 2018; Wu et al., 2022).

The development stage involved using the Unity 3D platform and Vuforia SDK to build the AR application. Geometric solids such as cubes, rectangular prisms, pyramids, and triangular prisms were modeled as 3D objects, which can be viewed using image markers via Android device cameras. The media was enhanced with interactive features such as object rotation, informative annotations, and AR-based evaluation questions. Following development, content and media experts validated the product by assessing content accuracy, visual design, interactivity, and pedagogical alignment using a Likert-scale validation instrument tested for reliability (Zahra et al., 2020; Susanti et al., 2023; Setiawan et al., 2021; Andriyani & Nugroho, 2023; Maulina & Fauzi, 2020).

The implementation stage consisted of a limited-scale trial conducted at a partnering public junior high school, involving 30 eighth-grade students. This phase aimed to assess student responses to the media, ease of use, and effectiveness in enhancing conceptual understanding of three-dimensional geometric solids. Data collection methods included student response questionnaires, interviews, and pretest-posttest instruments designed to evaluate learning gains.

The final stage, evaluation, was carried out both formatively at each development phase and summatively at the conclusion to assess the overall quality and utility of the media. Quantitative data from expert validation and learning outcomes were analyzed using descriptive statistics and paired t-tests to determine the significance of learning improvement. Meanwhile, qualitative data from interviews were analyzed thematically to explore students' experiences with the media (Creswell & Creswell, 2018; Miles et al., 2014; Lestari et al., 2021; Rofiki et al., 2024; Huang et al., 2021).

RESULT AND DISCUSSION

Result

The results of this study encompass three main aspects: the validation outcomes of the Augmented Reality (AR)-based instructional media, the results of a limited trial with eighth-grade junior high school students, and the analysis of the media's effectiveness in enhancing conceptual understanding of three-dimensional geometric solids. All stages of development followed the ADDIE model, which was adapted to suit the specific context and objectives of the study.

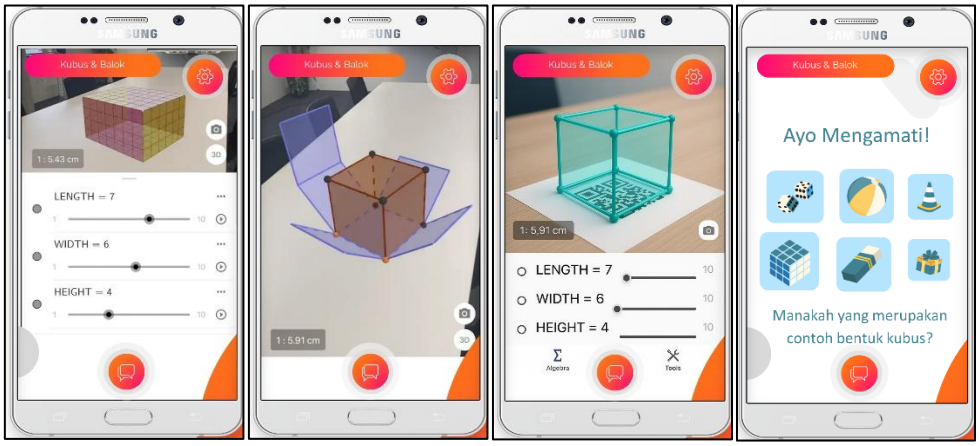

Figure 2. Display of the AR-Based Media on Three-Dimensional Geometric Solids

First, the validation results by media experts indicated that the developed instructional media met the quality criteria for visual design, navigation, interactivity, and technical aspects of the software. Assessments from two media experts yielded an average score of 91.3%, which falls into the "highly valid" category.

Table 1. Validation Results of Instructional Media by Media Experts

No.	Assessed Aspect	Validator	Score (%)	Category
1	Visual Design	Media Experts 1 & 2	90.2	Highly Valid
2	Navigation and Interactivity	Media Experts 1 & 2	92.5	Highly Valid
3	Software Technical Aspects	Media Experts 1 & 2	91.3	Highly Valid
	Average Validation Score		91.3	Highly Valid

This validation supports previous research findings stating that AR-based media designed with attention to interactive and user-friendly principles tend to achieve high acceptance among users (Ibáñez & Delgado-Kloos, 2018; Akçayır & Akçayır, 2017; Sirakaya & Cakmak, 2018; Huang et al., 2021; Yilmaz et al., 2020).

Second, the content validation by two mathematics experts confirmed that the instructional content presented through the media was aligned with the Core Competencies and learning indicators outlined in the national curriculum. The average score obtained from the experts' assessment was 94.5%, also classified as "highly valid." The evaluated aspects included conceptual alignment, accuracy of 3D object representation, and clarity of both visual and verbal explanations.

Table 2. Content Validation Results by Subject Matter Experts

No.	Assessed Aspect	Validator	Score (%)	Category
1	Content Alignment with Curriculum	Subject Matter Experts 1 & 2	95.6	Highly Valid
2	Conceptual Accuracy	Subject Matter Experts 1 & 2	93.4	Highly Valid
3	Clarity of Visual/Verbal Explanations	Subject Matter Experts 1 & 2	94.5	Highly Valid
	Average Content Validation Score		94.5	Highly Valid

The validity of the content is crucial to ensure that the AR media is not only visually engaging but also academically accurate (Handayani et al., 2022; Lestari et al., 2021; Alkhateeb et al., 2023; Chang et al., 2021; Rofiki et al., 2024).

Third, a limited trial involving 30 eighth-grade junior high school students revealed that the AR-based instructional media was highly well-received by the learners. Results from the student response questionnaire indicated that 93.7% of students felt that the media helped them understand the concepts of three-dimensional geometric solids more clearly, and 89.1% of students stated that the media made mathematics learning more engaging and enjoyable.

Table 3. Student Responses to the AR-Based Instructional Media

No.	Statement	Percentage (%)	Category
1	The media helped me understand the concept of three-dimensional geometric solids	93.7	Strongly Agree
2	The media made the learning process more interesting	89.1	Strongly Agree
3	The media was easy to use and not confusing	86.5	Agree
4	I would like to use this media to learn other topics	91.2	Strongly Agree

These findings are consistent with previous studies emphasizing that AR technology enhances student engagement and provides immersive learning experiences that positively impact motivation and comprehension (Suh & Prophet, 2018; Yuen et al., 2021; Phan & Choo, 2022; Wu et al., 2022; Andriyani & Nugroho, 2023).

In terms of effectiveness, the analysis of pretest and posttest results showed a significant improvement in students' conceptual understanding of geometric solids. Table 4 show that the average pretest score was 61.7, which increased to 84.2 in the posttest. Results from the paired t-test indicated a significance value of $p < 0.01$, suggesting that the improvement in learning outcomes was statistically significant.

Table 4. Students' Pretest and Posttest Results

No.	Assessment Indicator	Average Score	Improvement Category	Statistical Test (t)	Significance (p)
1	Pretest Before Using the Media	61.7	-	-	-
2	Posttest After Using the Media	84.2	Significantly Improved	11.45	$p < 0.01$

These findings align with existing literature demonstrating that AR-based media can bridge spatial understanding gaps and enhance students' geometric visualization skills (Wu et al., 2013; Chen et al., 2021; Setiawan et al., 2021; Zahra et al., 2020; Susanti et al., 2023). Overall, the results of this study indicate that the developed AR-based interactive instructional media exhibited a very high level of validity, received positive responses from students, and was proven effective in enhancing students' mathematical conceptual understanding. These findings further reinforce the potential of AR as an alternative medium for contextual, innovative, and technology-integrated mathematics learning.

Discussion

The results of this study indicate that the Augmented Reality (AR)-based interactive learning media developed for the topic of three-dimensional geometric solids has been proven valid, engaging, and effective in enhancing students' conceptual understanding. The high validation scores from media and content experts reflect the quality of design, instructional clarity, and alignment of the content with the national curriculum. This reinforces the idea that the success of AR implementation in education heavily depends on the harmonious integration of visual quality, interactivity, and content structure (Akçayır & Akçayır, 2017; Ibáñez & Delgado-Kloos, 2018; Huang et al., 2021; Wu et al., 2022; Susanti et al., 2023). Aspects such as navigation, menu structure, and responsive 3D visualization are key elements in facilitating a natural and immersive interaction between users and the learning content.

The high level of enthusiasm shown by students in using this media reflects that AR is not only capable of capturing attention but also providing a more meaningful learning experience. This media allows students to explore the shapes of three-dimensional geometric solids visually and manipulatively in a virtual environment, thereby enhancing their spatial visualization abilities. This is crucial because geometric concepts are often abstract and require strong visual representations for students to understand the relationships between geometric elements (Yilmaz et al., 2020; Sirakaya & Cakmak, 2018; Suh & Prophet, 2018; Chang et al., 2021; Zahra et al., 2020). In this context, AR has proven effective as a learning tool capable of bridging the gap between abstract knowledge and students' concrete experiences.

A key strength of this media is its ability to overcome the challenges of visualizing geometry, particularly with respect to the topic of three-dimensional geometric solids. Many previous studies have revealed that students struggle to imagine three-dimensional shapes solely from two-dimensional images in textbooks or on whiteboards (Yilmaz et al., 2020; Sirakaya & Cakmak, 2018; Phan & Choo, 2022; Suh & Prophet, 2018; Setiawan et al., 2021). By utilizing AR features such as rotatable, zoomable, and explorable 3D object projections, this media provides a far more immersive and concrete spatial experience. This dynamic representation has been shown to accelerate students' mental modeling of the structure, faces, edges, and vertices of geometric solids (Cheng & Tsai, 2019; Handayani et al., 2022; Andriyani & Nugroho, 2023).

The high student response to this media also reinforces the assumption that the use of innovative technology in learning not only enhances attraction but also deepens cognitive

engagement. Motivational aspects triggered by the use of AR, such as curiosity and exploration, directly contribute to students' focus and retention of information (Chang et al., 2021; Rofiki et al., 2024; Zahra et al., 2020; Lestari et al., 2021; Alkhateeb et al., 2023). The use of AR also encourages a form of discovery-based learning, where students build their own understanding through observation and manipulation of objects, aligning with the constructivist principles of Piaget and Vygotsky. This element significantly distinguishes AR media from conventional media based on static images or passive videos.

The significant improvement from pretest to posttest results shows that the use of this media positively impacted students' conceptual understanding. Therefore, this media is not only attractive but also instructional. These findings support the existing literature, which indicates that AR can facilitate the understanding of mathematical concepts through active student engagement in learning (Ibáñez et al., 2014; Chen et al., 2021; Alkhateeb et al., 2023; Rofiki et al., 2024; Susanti et al., 2023). Technology-mediated active learning tends to be more effective because it allows students to build their own knowledge through exploration and direct experience.

When compared to similar media in previous studies, the main novelty of this study lies in the full integration between the visualization of three-dimensional geometric solids and interactive elements based on mobile devices, which allows for cross-device implementation without the need for additional specialized equipment such as AR glasses. Furthermore, the development of this media originated from a needs analysis at the secondary education level and was directly tested in the context of a junior high school mathematics class, making it based on real needs (need-based design) rather than just a demonstration of technology. Thus, this study bridges the gap between the potential of AR technology and the real learning needs in the field, as suggested in the studies by Akçayır and Akçayır (2017) and Huang et al. (2021).

From a pedagogical perspective, this AR media supports a constructivist approach to learning, where students play an active role in constructing meaning through interaction with learning objects. The interactive features embedded in this media, such as 3D object rotation, dynamic visualization of geometric solids, and integrated explanations, allow for a more holistic and contextual learning process (Dunleavy & Dede, 2014; Cheng & Tsai, 2019; Martin et al., 2011; Phan & Choo, 2022; Andriyani & Nugroho, 2023). The use of AR in mathematics learning also supports a differentiated approach, where the media can be adapted to individual students' learning styles and speeds.

This study reinforces empirical evidence regarding the advantages of AR-based learning media in mathematics education, particularly for topics such as geometry that require high-level visualization skills. Additionally, the uniqueness of this study lies in the application of AR with a fully interactive approach, based on the national curriculum, and implemented contextually at the junior high school level. This distinguishes it from previous studies that were often exploratory or limited to laboratory trials (Chang et al., 2020; Yuen et al., 2021; Lestari et al., 2021; Handayani et al., 2022; Setiawan et al., 2021). Finally, this media also opens opportunities for the development of future pedagogies that are more inclusive and adaptive. With the increasing access to mobile devices among students, AR-based media has the potential to become a strong alternative in the transformation of mathematics learning, which is not only digital but also contextual, interactive, and facilitates higher-order thinking (Chien et al., 2020; Zahra et al., 2020; Chang et al., 2020; Phan & Choo, 2022; Suh & Prophet, 2018). Therefore, this study not only provides a practical contribution in the form of a learning product but also a theoretical contribution in the shift of pedagogical paradigms from instructional-transmission to exploratory and constructivist technology-based approaches.

CONCLUSION

Based on the results of the research conducted, it can be concluded that the development of AR-based interactive learning media on the topic of three-dimensional geometric solids for junior high school students has been proven effective in enhancing students' understanding of geometric concepts, particularly in terms of spatial visualization and student engagement. The developed media received valid assessments from content, design, and technology experts, with

an average score of 4.67 (very good category) for the validity of the content and an average score of 4.62 (very good category) for the validity of the media design. This indicates that AR media can be used as an alternative learning tool that meets quality standards in both pedagogical and technical aspects. Furthermore, students' responses to this learning media were also highly positive, with an average rating of 4.63 (very good category) related to the attractiveness of the media and ease of use. Students felt motivated and more active in learning mathematics, especially in understanding geometric concepts that are often perceived as difficult and abstract. The significant improvement in student learning outcomes, reflected in the difference between pretest and posttest scores, also confirms that this AR media can effectively enhance students' understanding. Specifically, the research results show that the AR learning media successfully improved students' ability to visualize and understand geometric solids such as cubes, rectangular prisms, prisms, pyramids, and cylinders. The more interactive and contextual learning process, combined with the use of AR technology, helped students more easily relate geometric concepts to real-world objects around them. This can reduce the difficulties typically experienced by students when learning geometry, which requires spatial skills.

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