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Augmented reality Mathematics media for enhancing critical thinking and motivation in elementary students

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ABSTRACT

The rapid advancement of information and communication technology in the digital era has transformed many sectors, including education. In line with Society 5.0 demands, education is expected to integrate technology into learning to foster students' critical thinking and motivation. This study aims to develop Augmented Reality (AR)-based Mathematics learning media using the Assemblr EDU application to enhance elementary students' critical thinking and motivation. The research employed the Research and Development (R&D) method, utilizing the ADDIE model (Analysis, Design, Development, Implementation, and Evaluation). Data were collected through interviews, questionnaires, and tests. The media's effectiveness was tested using a quasi-experimental design with a non-equivalent control group. Results show that AR-based Mathematics media are technically and pedagogically valid and effectively improve students' critical thinking and motivation. Expert validation confirmed its feasibility with minor revisions, and effectiveness testing showed significant advantages over conventional methods. AR enables interactive visualization of spatial concepts, supports concept identification and clarification, and creates an engaging learning experience. In conclusion, integrating AR technology into Mathematics learning offers an innovative solution to enhance numeracy literacy and meet 21st-century learning challenges in elementary schools.

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ABSTRAK

Kemajuan pesat teknologi informasi dan komunikasi di era digital telah mentransformasi berbagai sektor, termasuk pendidikan. Sejalan dengan tuntutan Society 5.0, dunia pendidikan dituntut untuk mengintegrasikan teknologi dalam proses pembelajaran guna mendorong kemampuan berpikir kritis dan motivasi belajar peserta didik. Penelitian ini bertujuan mengembangkan media pembelajaran matematika berbasis Augmented Reality (AR) menggunakan aplikasi Assembler EDU untuk meningkatkan kemampuan berpikir kritis dan motivasi belajar siswa sekolah dasar. Metode yang digunakan adalah Research and Development (R&D) dengan model ADDIE (Analysis, Design, Development, Implementation, and Evaluation). Data dikumpulkan melalui wawancara, kuesioner, dan tes. Efektivitas media diuji menggunakan desain kuasi-eksperimen dengan kelompok kontrol non-ekuivalen. Hasil penelitian menunjukkan bahwa media pembelajaran matematika berbasis AR dengan Assembler EDU valid secara teknis dan pedagogis serta efektif dalam meningkatkan kemampuan berpikir kritis dan motivasi belajar siswa sekolah dasar. Validasi ahli menunjukkan media layak digunakan dengan revisi minor, dan uji efektivitas membuktikan keunggulan signifikan dibandingkan metode konvensional. Penggunaan AR memungkinkan visualisasi konsep bangun ruang secara interaktif, mendukung proses identifikasi dan klarifikasi konsep matematika, serta menciptakan pengalaman belajar yang menarik. Kesimpulannya, integrasi teknologi AR dalam pembelajaran matematika merupakan solusi inovatif untuk meningkatkan literasi numerasi serta menjawab tantangan pembelajaran abad ke-21 di sekolah dasar.

Kata Kunci: *augmented reality; media pembelajaran Matematika; motivasi belajar; pemikiran kritis; pendidikan dasar*

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INTRODUCTION

The rapid development of Information and Communication Technology (ICT) in today's digital era has profoundly transformed various aspects of human life, including education. Technology provides numerous innovations that facilitate daily human tasks and are increasingly integrated into teaching and learning processes. Technology is no longer merely a support tool but has become a strategic means to achieve educational goals (Jeong & Hmelo-Silver, 2016). Educational technology is a complex and abstract concept, involving various elements that work together to identify problems, deliver content, and evaluate learning outcomes (Bond et al., 2020). In this context, ICT serves not only to support the educational process but also to enhance learning outcomes, especially in terms of quality, efficiency, and accessibility at all levels of education. This broader perspective underscores the transformative impact of ICT on education.

Technology in education enables teachers to align learning content and teaching methods with students' individual needs, facilitates collaboration, supports project-based learning, streamlines assessment processes, and enables distance learning (Baroroh et al., 2024). Technology also plays a role in fostering active learning, collaboration, and knowledge creation among students (Khan et al., 2017). The demands of the twenty-first century and Society 5.0 require education to adapt to the integration of advanced technologies, such as Artificial Intelligence (AI), Virtual Reality (VR), and Augmented Reality (AR). Among these, AR is a promising educational tool that combines real-world and virtual elements in real-time, enabling immersive and engaging learning experiences (Judijanto et al., 2024). AR has the potential to improve student attention, foster critical thinking, and make complex or abstract topics more concrete and accessible (Alkhabra et al., 2023).

Building on this potential, previous studies have investigated the impact of AR in various educational contexts. Several studies have demonstrated the effectiveness of AR in learning. AR has been shown to significantly improve junior high school students' geometry thinking skills and enhance students' critical thinking abilities (Pujiastuti & Haryadi, 2024; Widianto et al., 2024). AR-based learning media for three-dimensional geometry have proven effective in secondary school settings (Listiawan et al., 2017). However, most of these studies have not focused on primary school students or on combining AR with both critical thinking and learning motivation. This indicates a research gap concerning the integration of AR-based learning in primary school settings that supports both critical thinking and learning motivation simultaneously. Preliminary observations in elementary schools in Pangebatan Village revealed that many teachers still rely heavily on lecture-based teaching and rarely use digital learning tools. Most educators are also unfamiliar with educational platforms provided by the Ministry of Education and are unaware of AR-based media such as Assemblr EDU.

In addition, the results of the *Asesmen Nasional Berbasis Komputer* (ANBK) indicate that several elementary schools perform poorly in numeracy, particularly in areas related to mathematical reasoning and problem-solving. This underscores the need for alternative teaching strategies and learning media to enhance students' understanding of geometry, critical thinking skills, and learning motivation. To address these gaps, this research aims to develop and test an AR-based Mathematics learning media for primary school students using

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Assemblr EDU. Specifically, this research aims to develop AR-based Mathematics learning media using Assemblr EDU for geometry topics that are valid and feasible both technically and pedagogically. Furthermore, this study also aims to examine the effectiveness of AR-based learning media in improving primary school students' critical thinking skills. Finally, this research seeks to investigate the efficacy of AR-based learning media in enhancing the motivation of primary school students. The focus is on three-dimensional shapes (solid figures) as part of the geometry content, which is often difficult for students to understand using conventional instructional approaches.

LITERATURE REVIEW

Instructional Media

Instructional media play a pivotal role in the teaching and learning process. The term "media" originates from the Latin word *medius*, meaning "middle" or "intermediary". Instructional media are essential components that influence the quality of teaching and learning outcomes (Abdulrahaman et al., 2020). Instructional media are defined as all tools and materials that support the delivery of learning content, including human resources, printed materials, audio recordings, video content, interactive platforms, or real-world objects (Mallillin, 2024). Instructional media can be classified into several categories based on the sensory channels and technologies they employ. These categories include audio media, which rely on auditory stimuli such as recordings; visual media, which present visual stimuli such as photos and diagrams; audio-visual media, which integrates both sound and images through videos; and digital media, which leverage interactive technologies including multimedia applications, AR, VR, and game-based learning (Reyna et al., 2017). Technology-enhanced media such as interactive multimedia and AR can make abstract concepts more understandable, which is especially useful in teaching Mathematics (Nicolaou et al., 2019).

Augmented Reality in Education

Augmented Reality (AR) is a technology that integrates virtual content (2D or 3D) into the real-world environment in real-time. AR is defined as an environment that merges the real and the virtual, with minimal boundaries between the two (Syed et al., 2022). It enables learners to visualize complex and abstract concepts, such as the inner workings of machines or geometric structures, thus improving comprehension and retention (Ziatdinov & Valles Jr, 2022). The advantages of AR in education include capturing students' attention, providing access to content anytime via mobile devices, stimulating critical thinking, and helping students retain information for extended periods. Moreover, AR enhances students' interest in learning new concepts and supports independent learning (Wibowo et al., 2022). Several studies support the effectiveness of AR-based learning media. For example, AR through GeoGebra has been shown to improve spatial intelligence in Mathematics learning (del Cerro Velázquez & Morales Méndez, 2021). AR-based interactive media has also been found to improve students' critical thinking skills (Syawaludin & Rintayati, 2019). However, most of these studies are conducted at secondary or vocational education levels, rather than in elementary schools.

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Mathematics Learning in Elementary School

Mathematics is a formal and abstract science that involves logic, structure, numbers, patterns, and spatial reasoning (Kusmaryono et al., 2018). Based on Piaget's cognitive development theory, elementary school students (aged 7–12) are in the concrete operational stage, meaning they learn best through real, tangible experiences rather than abstract reasoning (Decano, 2017). In elementary education, Mathematics instruction should focus on developing pattern recognition, problem-solving skills, creativity, and mathematical communication (Khalid et al., 2020). The geometry curriculum, especially three-dimensional shapes (solid figures), often presents difficulties for students due to its abstract nature. Integrating AR can offer more concrete, visual, and interactive representations of these mathematical objects (İbili et al., 2020).

Critical Thinking

Critical thinking refers to the ability to reflect, analyze, and evaluate information logically in order to make well-reasoned judgments. It is defined as the capacity for reflective and problem-solving thought, and it plays a pivotal role in producing logical, systematic, and productive conclusions (Rahardhian, 2022). The core indicators of critical thinking include interpretation, analysis, evaluation, inference, and explanation (Sutiani, 2021). Cultivating students' critical thinking skills is essential for preparing them to navigate complex real-world challenges and to engage in informed decision-making. In the educational context, it fosters active engagement, encouraging students to move beyond passive absorption of knowledge toward becoming independent and analytical learners (Wardani, 2023).

Learning Motivation

Motivation is a critical factor in achieving effective learning. It is defined as a complex internal drive that directs individual behaviour toward specific goals (Hafid, 2017; Sya'ro & Dewi, 2022). Learning motivation refers to the internal or external impulses that energize students to engage in and persist with learning activities (Seven, 2020). Motivation can be intrinsic, driven by personal interest or internal goals, or extrinsic, driven by external rewards or expectations. Indicators of learning motivation include interest, persistence, desire for success, engagement in tasks, and enjoyment of learning (Febriani et al., 2022). A motivated student is more likely to develop critical thinking skills and actively participate in the learning process. Integrating technology such as AR can stimulate both intrinsic and extrinsic motivation, especially when the media is interactive, immersive, and tailored to students' needs and interests. This highlights the important role of AR in enhancing student engagement and motivation through meaningful digital experiences (Pellas et al., 2019).

METHODS

This study employed a Research and Development (R&D) approach incorporating the ADDIE model, which consists of five stages: Analysis, Design, Development, Implementation, and Evaluation. To assess the effectiveness of the developed product, a quasi-experimental design with a nonequivalent pretest-posttest control group was employed, enabling

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comparisons of learning outcomes between groups over time. The research was conducted at two public elementary schools in the Bantarkawung District, Brebes Regency: SDN Pangebatan 05, serving as the experimental group, and SDN Pangebatan 07, serving as the control group. The sample comprised 42 sixth-grade students (23 in the experimental group and 19 in the control group), selected through purposive sampling based on equivalent academic abilities and access to technology. This ensured baseline equivalence across groups, supporting the internal validity of the study. In the Analysis phase, classroom observations and interviews with teachers were conducted to identify instructional challenges in teaching geometry.

Students' characteristics were examined in relation to Piaget's cognitive development theory, and the learning content focused on three-dimensional shapes, aligning with Phase C of the Merdeka Curriculum. During the Design and Development phases, AR-based Mathematics learning media were developed using the Assemblr EDU platform. The media were validated by experts in instructional media, Mathematics content, and elementary education to ensure pedagogical and technological feasibility. A small-scale trial was also conducted with sixth-grade students outside the main sample to assess clarity, usability, and practicality without interfering with the primary experimental group. In the Implementation phase, the experimental group was taught using the AR-based media, while the control group received instruction using conventional teaching methods. Both groups followed a structured learning plan with identical content based on a standardized module.

Following the instructional sessions, all students completed a posttest on critical thinking and a learning motivation questionnaire. Validation sheets were also administered to assess the feasibility of the media according to expert judgment. To determine the effectiveness of the AR-based media, descriptive and inferential statistical analyses were performed. The Kolmogorov–Smirnov test was conducted to check data normality, and Levene's test was used to assess the homogeneity of variances. An independent-sample t-test was then conducted to compare the post-test scores of the experimental and control groups. These procedures were chosen because they are appropriate for examining differences between two independent groups in a quasi-experimental design. Finally, in the Evaluation phase, the data obtained were analyzed both quantitatively and qualitatively to assess the effectiveness of AR media in enhancing students' critical thinking skills and learning motivation. Statistical tests were used to identify the differences in outcome measures between groups, while qualitative feedback was examined to inform potential improvements in the developed product.

RESULTS AND DISCUSSION

This chapter presents the study's findings, based on data collected from the experimental and control classes. The results are divided into media validation findings, critical thinking performance, and learning motivation outcomes.

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Media Expert Validation

The media expert validation questionnaire was administered to a media expert on March 25, 2025. The questionnaire covered various components, including audiovisual aspects and other relevant criteria. The results are summarized in **Table 1**.

Table 1. Media Expert Validation Results

No	Assessed Aspects	Description
Audio Visual Aspect		
1	Appropriateness of image usage in the media	Image usage is appropriate
2	Appropriateness of color usage in the media	Color usage is appropriate
3	Appropriateness of font style used in the media	Font usage is appropriate
4	Appropriateness of font size used in the media	Font size is appropriate
5	Word usage in the media	"About Me" can be changed to "Biography"
6	Use of capital letters in the media	Use of capital letters is appropriate
7	Use of font color in the media	Font and size can be enlarged and clarified; the text in the material can be adjusted to use a single, consistent color
8	Use of line spacing in the media	Line spacing usage in the media is appropriate
9	Use of image animation in the media	Image animations are appropriate and easy to understand
11	Clarity of text in the media	The text in the media is clear
12	Clarity and accuracy of audio in the media	The text in the media is clear
14	Alignment between the design layout and text placement	The layout and text placement are appropriate
15	Completeness and structured organization of media content	The content in the media is complete
17	Simplicity and user-friendliness of the media	The media is easy to use
18	Availability of navigation buttons in the media	Navigation buttons, such as "next" can be replaced with symbols to help students better understand their function
Other Aspects		
20	The media is communicative	The media is highly communicative
21	The media can be used independently without expert assistance	The media can be used independently by students, particularly in upper-grade levels
22	The language used in the media is easy to understand	The language used is appropriate
23	The media requires action and extensive information processing to solve mathematical problems	Highly appropriate; includes an evaluation component

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No	Assessed Aspects	Description
24	The media supports the evaluation of students' critical thinking skills	Highly appropriate

Source: Author Documentation 2025

As shown in **Table 1**, the majority of the assessed aspects of the augmented reality (AR)-based Mathematics learning media. This indicates that, overall, the media were well-designed and aligned with pedagogical standards. The expert concluded that the AR-based media is feasible for classroom implementation, although several minor revisions were suggested to enhance its usability and clarity. Among these suggestions were the replacement of the label "About Me" with the more academically appropriate term "Biography," the use of larger and more uniform font sizes and colors to improve visual consistency, and the substitution of text-based navigation buttons like "next" with more intuitive symbols, such as arrows, to support ease of use and reduce cognitive load for students. These recommendations aimed to refine the user interface to better accommodate student needs and enhance their learning experience. Following this expert validation, the next phase of the study focused on evaluating the effectiveness of the AR-based media in fostering students' critical thinking skills.

Effectiveness of Media on Critical Thinking

The AR-based media was tested on two groups: an experimental class (n = 23) and a control class (n = 19). Both groups followed the same learning module. The experimental class utilized AR-based media on April 18, 2025, while the control class was taught conventionally on the same date. Posttest data showed differences in students' critical thinking scores. The average posttest critical thinking scores for the two groups are displayed in **Figure 1**.

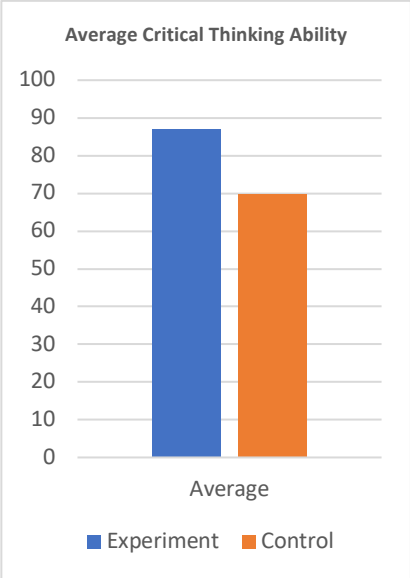

Figure 1. Average Critical Thinking Ability
Source: Author Documentation 2025

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As shown in **Figure 1**, the experimental class achieved a higher average critical thinking score of approximately 87, while the control class achieved an average score of approximately 70. This 17-point difference suggests that students in the experimental class demonstrated stronger critical thinking skills compared to those in the control class. The improvement in the experimental group can be attributed to the integration of AR-based Mathematics learning media into the instructional process. Meanwhile, the control class was taught using conventional methods without the use of AR. Both groups used the same learning module developed by the researcher and completed the session with a posttest to assess critical thinking skills, as well as a learning motivation questionnaire.

In the experimental class, AR content was embedded through the use of QR codes, which students scanned using smartphones or laptops, allowing them to access interactive media during the learning activities. On the other hand, in the control class, instruction was delivered using traditional methods with the aid of a television to display materials, but without the support of interactive AR elements. Additionally, students' performance across the five critical thinking indicators (identifying, clarifying, analyzing, evaluating, and concluding) was examined. The percentage achievement for each indicator is summarized in **Figure 2**.

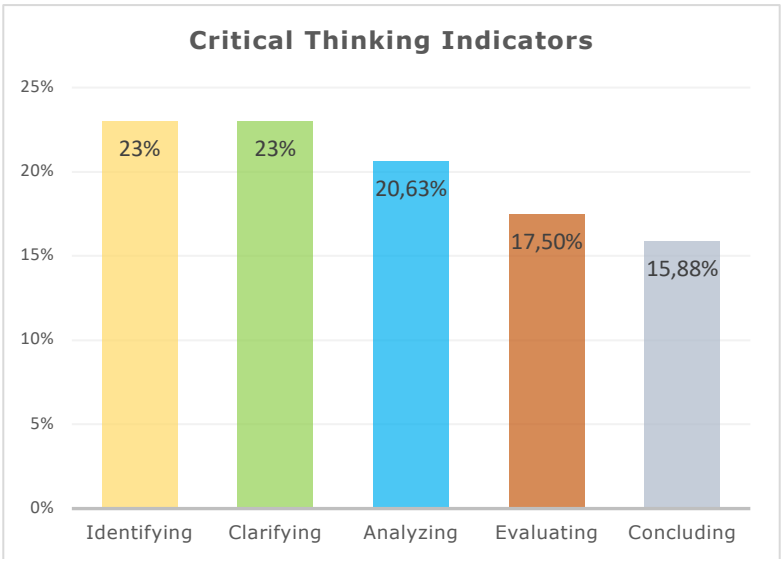

Figure 2. Indicator-wise Achievement of Critical Thinking Skills Using AR Media
Source: Author Documentation 2025

Figure 2 illustrates the indicator-wise achievement of students' critical thinking skills in the experimental class that used AR-based learning media. Among the five indicators, students demonstrated the highest achievement in the identifying and clarifying indicators, each at 23%. This suggests that AR media effectively supports students in recognizing and understanding mathematical problems. The analysis indicator followed with a score of 20.63%, indicating that students were moderately able to break down information and examine relationships.

Meanwhile, evaluating (17.5%) and concluding (15.88%) scored slightly lower, indicating that higher-order critical thinking tasks, such as making judgments and drawing conclusions, may require more guided practice, even with AR assistance. These results indicate that AR media particularly enhance students' foundational critical thinking processes, such as

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identifying and clarifying information. To further understand the media's impact beyond cognitive outcomes, it is also essential to examine its effect on students' affective domain, particularly their learning motivation, as presented in **Figure 3**.

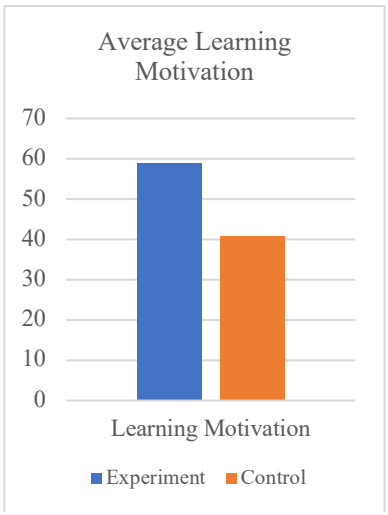

Figure 3. Average Learning Motivation
Source: Author Documentation 2025

Figure 3 shows the average learning motivation scores between the experimental and control classes. The experimental class, which used AR-based learning media, scored significantly higher, with an average of around 60, compared to the control class's score of around 40. This difference indicates that integrating interactive and immersive elements through AR can enhance student engagement and motivation during the learning process.

The visual and spatial interactions provided by AR can stimulate curiosity, maintain attention, and make abstract mathematical concepts more concrete and meaningful to students. These findings indicate that AR media not only contribute to improving learning outcomes in general, but also influence affective aspects such as student learning motivation. To gain a deeper understanding, **Figure 4** presents student achievement on each learning motivation indicator.

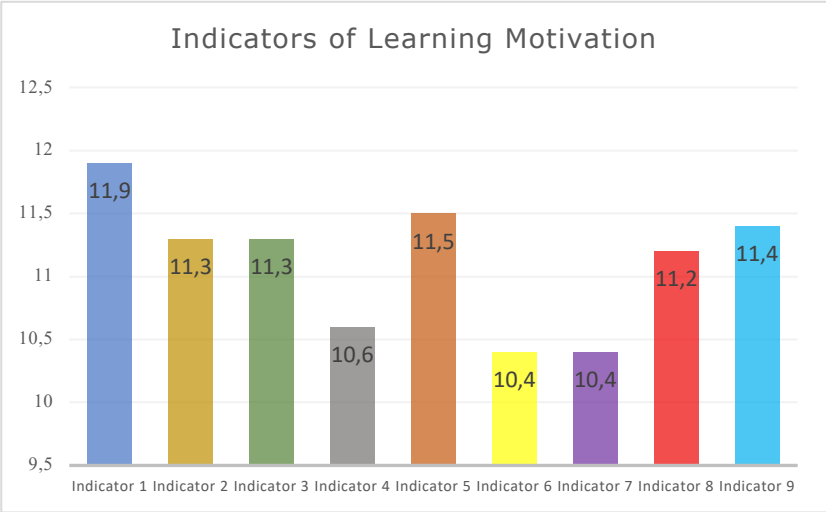

Figure 4. Achievement on Each Learning Motivation Indicators
Source: Author Documentation 2025

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Figure 4 displays student achievement on nine learning motivation indicators after using Augmented Reality-based learning media. From the graph, it can be seen that Indicator 1 obtained the highest score of 11.9, followed by Indicator 4 (11.5) and Indicator 9 (11.4). This achievement reflects a strong initial drive to learn, as well as increased student interest and participation in the learning process.

Meanwhile, indicators 6 and 7 showed the lowest scores, each at 10.4, indicating that students still face challenges in aspects such as perseverance and consistency in completing learning tasks. However, the difference between the scores of each indicator is not too significant, indicating that, in general, students show a good level of motivation in all aspects. Overall, these results strengthen previous findings that the use of AR-based media in learning can have a positive impact not only on cognitive aspects but also on students' overall learning motivation.

Discussion

Media Expert Validation

The media expert validation results demonstrated that the AR-based Mathematics learning media met professional standards for the implementation of educational technology. The validation process by a media expert revealed that most assessed aspects received "appropriate" or "highly appropriate" ratings across audiovisual and pedagogical components. This finding aligns with established criteria for educational media development, where expert validation serves as a critical quality assurance mechanism (Reyna et al., 2017). The expert's suggestions for improvement, including terminology refinement ("About Me" to "Biography"), enhanced visual consistency through uniform font usage, and intuitive navigation design through the use of symbolic representations, reflect current best practices in user interface design for educational applications. These recommendations align with the principles of cognitive load theory, which emphasizes the importance of reducing extraneous cognitive load to optimize learning (Skulmowski & Xu, 2022). The feasibility rating of "suitable for use with revisions" indicates that the AR media successfully met the minimum threshold for classroom implementation while providing clear pathways for enhancement.

Critical Thinking Skills Enhancement

The experimental results revealed a significant 17-point difference in critical thinking scores between the experimental class (M = 87) and the control class (M = 70), demonstrating the effectiveness of AR-based learning media in enhancing students' critical thinking capabilities. This finding is consistent with previous research indicating that the integration of digital media has a significant influence on the development of elementary students' critical thinking (Encabo-Fernández et al., 2023). The substantial score difference suggests that AR technology provides unique affordances for cognitive skill development that traditional instructional methods cannot replicate. The indicator-wise analysis revealed differential impacts across the five dimensions of critical thinking. The highest achievement in identifying (23%) and clarifying (23%) indicators demonstrates AR media's particular strength in supporting foundational cognitive processes.

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This pattern aligns with research showing that AR media enhances students' spatial understanding through interactive visualization and multiple perspective viewing (Ashari, 2023; Hasannah et al., 2024; Yasmin, 2023). The technology's ability to present three-dimensional mathematical concepts in manipulable virtual environments appears particularly beneficial for recognition and comprehension tasks. The moderate performance in the analyzing indicator (20.63%) suggests that AR media effectively supports information processing and relationship examination, though not to the same extent as basic recognition tasks. This finding is consistent with the hierarchical nature of critical thinking skills, where analytical processes require more sophisticated cognitive operations than identification tasks (List & Sun, 2023).

The relatively lower scores in evaluating (17.5%) and concluding (15.88%) indicators reflect the inherent complexity of higher-order thinking skills in elementary students. These results support the observation that AR technology is more effective for visual and exploratory skills than for evaluative thinking processes (Encabo-Fernández et al., 2023). The developmental limitations of elementary students in abstract reasoning and judgment formation may explain why AR's visual enhancements have less impact on these advanced cognitive processes. These findings confirm that AR-based Mathematics learning media have a positive impact on students' critical thinking development, which is consistent with previous research demonstrating AR's effectiveness in enhancing critical reasoning skills (Ermawati et al., 2024; Widianto et al., 2024). However, the variation in effectiveness across different thinking skill levels suggests that AR implementation should be complemented with explicit instruction in higher-order thinking strategies.

Learning Motivation Enhancement Discussion

The learning motivation analysis revealed an 18-point advantage for the experimental class (M = 59) compared to the control class (M = 41), indicating that AR-based learning media significantly enhanced students' motivational engagement. This finding corroborates research demonstrating the effectiveness of AR media in fostering learning motivation among elementary students (Putra et al., 2024). The indicator-specific analysis provided further insight into the motivational mechanisms underlying AR's effectiveness. The highest achievement in the "engaging activity" indicator reflects the capacity of AR technology to create immersive, interactive learning experiences through three-dimensional visualization and the manipulation of virtual objects. This aligns with previous research, which shows that students respond positively and with high enthusiasm to AR-based learning activities (Volioti et al., 2023). Similarly, the technology's ability to transform abstract mathematical concepts into tangible, manipulable virtual objects appears to naturally stimulate student interest and participation.

A strong performance in the "enjoyment in learning" indicator also supports the finding that AR-based media significantly attracts students' interest in teaching and learning (Ilma et al., 2022). By presenting realistic and interactive representations of learning objects, AR fosters positive emotional connections with mathematical content, which can, in turn, enhance students' intrinsic motivation for continued engagement with the subject. However, the analysis also revealed some implementation challenges. The relatively low achievement in the "reward in learning" indicator indicates that students did not receive adequate recognition

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for their participation and accomplishments during AR-based lessons. This suggests the need for integrating appropriate feedback and recognition systems into AR implementation, as motivational theories emphasize the crucial role of external validation in sustaining engagement (Barrick et al., 2015).

Similarly, the low score in the "conducive learning environment" indicator implies that technical limitations and insufficient teacher preparation hindered optimal implementation. This underscores the importance of adequate infrastructure and professional development for successful AR integration, which is consistent with research highlighting the socio-technical requirements of educational technology adoption (Wiziack et al., 2021). Overall, the comprehensive analysis across the nine motivation indicators outlined by Uno (2016) demonstrates that AR-based Mathematics learning media can foster multidimensional motivational engagement among elementary students. These findings suggest that, with careful attention to reward systems, learning environments, and teacher support structures, AR can be further optimized to maximize its motivational and educational benefits.

Implications and Theoretical Contributions

The study's findings contribute to the growing body of evidence supporting the pedagogical value of AR technology in elementary Mathematics education. The differential effectiveness observed across cognitive and motivational dimensions provides nuanced insights into AR's optimal applications and limitations. The research demonstrates that while AR excels in supporting foundational cognitive processes and intrinsic motivation, its implementation requires careful attention to instructional design and contextual factors. The results support constructivist learning theories by demonstrating how AR's interactive and visual capabilities enable students to actively construct mathematical understanding through the direct manipulation of virtual objects. The technology's effectiveness in enhancing identifying and clarifying skills particularly supports Piaget's emphasis on concrete operational thinking in elementary students. From a practical perspective, the findings suggest that AR-based learning media should be integrated strategically within broader pedagogical frameworks that explicitly address higher-order thinking skills and provide comprehensive motivational support systems. The research indicates that AR's technological affordances must be complemented by thoughtful instructional design and adequate implementation support to achieve optimal learning outcomes.

CONCLUSION

This research successfully developed and validated AR-based Mathematics learning media using Assemblr EDU for three-dimensional shapes in elementary education. The media expert validation confirmed the technical and pedagogical feasibility of the developed AR media, establishing its readiness for classroom implementation with minor revisions. The effectiveness testing demonstrated that AR-based learning media significantly enhance students' critical thinking skills and learning motivation compared to conventional teaching methods. Students using AR media showed superior performance in foundational critical thinking processes, particularly in identifying and clarifying mathematical concepts, while also demonstrating substantially higher levels of learning engagement and motivation. These

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findings address the educational challenges identified in Pangebatan Village, including poor ANBK numeracy performance and limited adoption of digital learning technologies. The research provides evidence that AR technology can serve as an effective solution for enhancing the quality of Mathematics education in Indonesian elementary schools, particularly in geometry instruction, where spatial visualization is crucial. The study contributes to the growing body of knowledge on the integration of educational technology in developing contexts, demonstrating that innovative digital tools can effectively bridge educational gaps when properly designed and implemented. Future research should focus on longitudinal studies to examine the sustainability of AR's impact on student learning outcomes and conduct large-scale implementation across diverse school contexts to test generalizability. Additionally, research is needed to develop effective teacher training models that address technology familiarity barriers in rural schools and investigate the economic feasibility of AR implementation in resource-constrained settings. Further studies should also explore adaptive AR systems that personalize learning experiences, compare the effectiveness of AR with other emerging educational technologies, and integrate mixed-methods approaches to gain deeper insights into student learning experiences with AR technology in Indonesian cultural contexts.

AUTHOR'S NOTE

The author declares that there is no conflict of interest related to the publication of this article. The author affirms that the data and content of the article are free from plagiarism.

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