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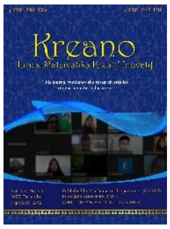

Interactive Visualization for Geometry Learning: The Impact of Augmented Reality on Students' Critical Thinking Skills

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Abstract

Students' critical thinking skills in geometry learning remain low due to the lack of visual media that can represent abstract concepts interactively and concretely. Conventional approaches often fail to stimulate students' cognitive engagement with geometric materials. This study aims to examine the impact of Augmented Reality (AR)-based media on enhancing students' critical thinking skills in geometry. A quasi-experimental method with a pretest-posttest control group design was employed, involving junior high school students in both experimental and control classes. The study employed a quasi-experimental design with a pretest–posttest control group, involving Grade VIII students from a public junior high school in Banten Province, with two intact classes consisting of approximately 30 students each assigned as the experimental and control groups. Data were collected using a critical thinking skills test covering interpretation, analysis, inference, evaluation, and explanation, supported by classroom observations and interviews. Data collection was conducted using multiple techniques to ensure data triangulation. Quantitative data were obtained through a critical thinking ability test administered as a pretest and posttest to both experimental and control groups. The test measured five indicators of critical thinking: interpretation, analysis, inference, evaluation, and explanation. Qualitative data were collected through structured classroom observations and semi-structured interviews with students and teachers. Data analysis involved descriptive statistics, N-Gain analysis to measure improvement, and qualitative thematic analysis of observation notes and interview transcripts to identify learning patterns related to critical thinking development.The results revealed a significant improvement in the critical thinking abilities of students in the experimental class, particularly in the indicators of analysis and evaluation. Augmented Reality–based geometry learning resulted in a substantially higher improvement in students' critical thinking skills (N-Gain = 0.75) compared to conventional learning (N-Gain = 0.32), indicating its superior effectiveness in enhancing students' abilities to interpret, analyze, infer, evaluate, and explain geometric concepts.It is concluded that AR visualization effectively supports a deeper and more critical understanding of geometry concepts. This study implies the importance of integrating AR technology into mathematics education to improve students' cognitive abilities and active learning.

Keywords: Augmented Reality; Critical Thinking; Geometry; Interactive Learning; Educational Visualization.

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Abstrak

Kemampuan berpikir kritis peserta didik dalam pembelajaran geometri masih tergolong rendah karena kurangnya media visual yang mampu merepresentasikan konsep-konsep abstrak secara interaktif dan konkret. Pendekatan konvensional sering kali gagal menstimulasi keterlibatan kognitif peserta didik terhadap materi geometri. Penelitian ini bertujuan untuk mengkaji pengaruh media berbasis Augmented Reality (AR) terhadap peningkatan kemampuan berpikir kritis peserta didik dalam pembelajaran geometri. Penelitian ini menggunakan metode kuasi eksperimen dengan desain pretest-posttest control group yang melibatkan peserta didik sekolah menengah pertama pada kelas eksperimen dan kelas kontrol. Penelitian melibatkan peserta didik kelas VIII dari sebuah sekolah menengah pertama negeri di Provinsi Banten, dengan dua kelas utuh yang masing-masing terdiri atas sekitar 30 peserta didik dan ditetapkan sebagai kelompok eksperimen dan kelompok kontrol. Data dikumpulkan menggunakan tes kemampuan berpikir kritis yang mencakup indikator interpretasi, analisis, inferensi, evaluasi, dan eksplanasi, serta didukung oleh observasi kelas dan wawancara. Pengumpulan data dilakukan melalui berbagai teknik untuk memastikan triangulasi data. Data kuantitatif diperoleh melalui tes kemampuan berpikir kritis yang diberikan sebagai pretest dan posttest kepada kelompok eksperimen dan kelompok kontrol. Tes tersebut mengukur lima indikator berpikir kritis, yaitu interpretasi, analisis, inferensi, evaluasi, dan eksplanasi. Data kualitatif dikumpulkan melalui observasi kelas terstruktur dan wawancara semi-terstruktur dengan peserta didik dan guru. Analisis data meliputi statistik deskriptif, analisis N-Gain untuk mengukur peningkatan kemampuan, serta analisis tematik kualitatif terhadap catatan observasi dan transkrip wawancara guna mengidentifikasi pola pembelajaran yang berkaitan dengan perkembangan kemampuan berpikir kritis. Hasil penelitian menunjukkan adanya peningkatan yang signifikan pada kemampuan berpikir kritis peserta didik di kelas eksperimen, terutama pada indikator analisis dan evaluasi. Pembelajaran geometri berbasis Augmented Reality menghasilkan peningkatan kemampuan berpikir kritis yang jauh lebih tinggi (N-Gain = 0,75) dibandingkan pembelajaran konvensional (N-Gain = 0,32), yang menunjukkan efektivitas yang lebih unggul dalam meningkatkan kemampuan peserta didik untuk menginterpretasikan, menganalisis, menginferensi, mengevaluasi, dan menjelaskan konsep-konsep geometri. Dapat disimpulkan bahwa visualisasi berbasis AR secara efektif mendukung pemahaman konsep geometri yang lebih mendalam dan kritis. Penelitian ini mengimplikasikan pentingnya integrasi teknologi AR dalam pendidikan matematika untuk meningkatkan kemampuan kognitif peserta didik dan mendorong pembelajaran yang lebih aktif.

INTRODUCTION

Mathematics is a basic science that is an important foundation in the development of science and technology (Pham et al., 2025). Among the branches of mathematics, geometry has a very important role in developing students' spatial thinking, visualization, and formal logic skills (Alam et al., 2025). Geometry is not only related to the recognition of shapes and sizes, but also involves understanding the properties of shapes, object transformations, and relationships between elements in a spatial system (Caswell et al., 2025; De La Rosa & Ruiz, 2025). Geometry is an important aspect of the junior high school curriculum since it serves as a foundation for students to comprehend advanced mathematical ideas (Pujiastuti & Haryadi, 2024).

Geometry enables pupils not only to recognize shapes and structures, but also to visualize objects, analyze spatial relationships, and build logical and inductive reasoning skills (Kim et al., 2025). Understanding geometric concepts demands good visualization and abstraction skills. Students must be able to imagine three-dimensional shapes from two-dimensional representations and understand geometric transformations, such as translation, rotation, reflection, and dilation (Wampler & Plecnik, 2025). Several research results demonstrate that geometry is one of the most difficult elements of mathematics for students to master, especially when learning is still dominated by traditional methodologies that are verbal and abstract without the aid of tangible imagery. (Alharbi, 2025).

Based on data from the recapitulation of final semester exam scores and formative assessments from a number of public junior high schools in Banten Province, the average student scores on geometry topics tend to stagnate and do not show significant improvement. The following data is a summary of the average value of students' geometry learning outcomes over the past five years.

Table 1. Geometry Result

Year	Average Geometry Score
2020	62.4
2021	58.1
2022	64.7
2023	60.3
2024	61.8

Analysis of the data shows that most students have not achieved optimal mastery of geometry concepts. Weaknesses in geometry mastery are often caused by a lack of in-depth spatial understanding and low student engagement in active and constructive learning processes (Zhu et al., 2025). Many students experience difficulty connecting geometric shapes with visual representations and their real-life applications (Libertus et al., 2024). Geometry skills that must be mastered by junior high school students include several basic competencies, including: (1) recognize and classify flat and spatial shapes based on their properties, (2) draw and manipulate geometric objects accurately, (3) understand and use relationships between angles, lines, and planes, and (4) apply geometry concepts in real life contexts, including spatial-based problem solving and decision making [11,12]. These competencies cannot be developed optimally without being supported by adequate critical thinking skills.

Critical thinking is the ability to objectively analyze information, evaluate arguments, make logical inferences, and formulate decisions based on valid reasoning (Rossouw & Steenkamp, 2025; Sireerat et al., 2025). In learning geometry, critical thinking skills play a central role because students are faced with situations that require concept exploration, proof, and conclusion-making. According to (Astutik et al., 2024), Critical thinking encompasses the dimensions of analysis, evaluation, inference, and explanation, all of which are important in understanding the structure of geometry, connecting visual and symbolic concepts, and solving problems rationally and reflectively.

In this context, critical thinking abilities must be cultivated during the geometry learning process. critical thinking skills involve the capacity to examine, evaluate, and derive logical conclusions from information (Zhang et al., 2025). In geometry learning, critical thinking helps students understand the definition of shapes, discern the characteristics of plane and solid shapes, determine the links between geometric elements, and evaluate the proof and problem-solving process. According to (X. Chen et al., 2024), critical thinking entails reflective and rational thinking in order to determine what to believe or do. The main problems related to critical thinking skills among secondary school students include low ability to interpret abstract geometric concepts, weak analytical reasoning, and difficulties in making logical inferences and explaining solutions. This study's pretest results indicate that students' average critical thinking scores were below 50, with the lowest performance occurring in the inference and explanation indicators, reflecting a tendency toward memorization-based learning rather than reflective and evidence-based reasoning. This ability is extremely important in geometry instruction since students must not only receive knowledge but also independently comprehend and evaluate the mathematical ideas offered.

Low critical thinking skills in geometry learning are inextricably linked to the traditional and teacher-centered learning strategy (Astutik et al., 2024). Teachers often dominate the learning process by lecturing, explaining procedures, and assigning repetitious assignments. Students tend to be passive consumers of information, with little opportunity to investigate, ask questions, argue, or construct arguments on their own. As a result, a learning technique is required that may stimulate students' cognitive participation in order to provide visual, interactive, and contextual learning experiences, one of which is the usage of Augmented Reality (AR) technology.

Augmented Reality is a technique that mixes virtual (digital) aspects with the real environment in real time using devices like smartphones or tablets (Rizki et al., 2025). This technology creates a more real, engaging, and interactive learning environment than traditional approaches. In geometry learning, AR allows students to directly observe, manipulate, and explore three-dimensional geometric objects, thus boosting their knowledge and involvement in the learning process. (Martín-Valero et al., 2025). AR can dynamically display visual representations of geometric shapes and transformations, allowing pupils to visually and instantaneously detect changes in the location and orientation of objects (Pujiastuti et al., 2024). Interacting with these visual items allows students to make direct observations, assess alternative solutions, and test theories, which is undoubtedly beneficial in strengthening their critical thinking skills (P.-J. Chen & Liou, 2023).

AR technology also promotes a constructivist learning model, where students become active subjects, constructing their knowledge through direct experience and reflection on the learning process (Ou Yang et al., 2023). From a constructivist perspective, successful learning occurs when students experience and interpret the topics they are learning themselves (Radu et al., 2023). AR enables learning by providing geometric objects that may be studied through direct touch, rotation, magnification, and alteration (Gao et al., 2023). In other words, this technology connects the abstract realm of mathematics to concrete experiences that students can have in real-life settings. Several studies have shown that using augmented reality in mathematics learning can boost students' motivation, conceptual knowledge, and higher-order thinking skills, including critical thinking (Othman et al., 2024).

Furthermore, the incorporation of augmented reality in geometry instruction is facilitated by (F. Yang & Wang, 2023) dual coding theory claims that information provided simultaneously via verbal and visual channels is processed more effectively by the brain. When children learn using complimentary text and visual representations, the information encoding process becomes richer and more meaningful. AR allows students to combine verbal material with spatial visuals, which improves their retention and comprehension of complicated geometric concepts. Furthermore, AR is consistent (O'Connor & Mahony, 2023) cognitive load theory, which emphasizes the necessity of lowering irrelevant cognitive load in learning. In math education, AR enables students to interact with three-dimensional geometric objects that can be rotated, expanded, or modified directly. Students may see and control geometric forms and transformations directly with AR, eliminating the need to envision them abstractly. This lessens students' mental workload and allows them to concentrate more on critical thinking when learning subjects.

According to (Pujiastuti & Haryadi, 2023a) using augmented reality in math education can considerably boost student enthusiasm and understanding. By seeing geometry objects in 3D, students may better understand the qualities and interactions between architectural pieces, as well as develop visualization and spatial reasoning skills (Pujiastuti & Haryadi, 2023c). This finding is corroborated by (Utomo et al., 2022), who declare that AR technology boosts cognitive engagement and improves students' academic achievement in the area of transformation geometry.

In addition to giving benefits in terms of visualization, augmented reality can help students improve critical thinking skills. AR exposes students to a variety of learning circumstances that demand independent inquiry, decision-making, observation of phenomena, and argumentation based on virtual objects (Pujiastuti et al., 2024; Pujiastuti & Haryadi, 2023c, 2022). AR's multimodal engagement encourages the brain to integrate information from multiple sources, improves learning, attention, and retention, and enables deeper meaning building (Haryadi & Pujiastuti, 2022; Pujiastuti & Haryadi, 2023a, 2024). According to (Rizki et al., 2025) augmented reality helps strengthen critical thinking skills, particularly in problem-based and inquiry learning. This technology creates an information-rich, visually appealing learning environment that encourages students to engage in active learning. In geometry, augmented reality serves as a link between abstract representations in books and actual representations that students can access and understand.

Background data from semester examination results and formative assessments show that students' average geometry scores over the last five years remained low and fluctuated between 58.1 and 64.7.Based on the background that has been described, the main problem in this study is related to the low critical thinking skills of students in understanding geometry concepts at the junior high school level, as well as the need for learning media innovations that are able to present interactive and contextual visualizations. This research is directed to answer the main question of whether there is a significant difference in critical thinking skills between students who learn using Augmented Reality-based learning media and students who learn through conventional approaches. In addition, this study also questions the extent of the influence of the use of Augmented Reality media on improving students' critical thinking skills in learning geometry. Another important aspect to be studied is which part of the critical thinking indicators-such as the ability to analyze, evaluate, and inference-that experienced the most significant improvement. This research also seeks to explore how students perceive the learning experience using Augmented Reality in understanding geometry concepts more deeply and critically.

The purpose of this study is to determine the effectiveness of the use of Augmented Reality-based learning media in improving the critical thinking skills of junior high school students on geometry material. Specifically, this study aims to analyze the differences in critical thinking outcomes between students who follow learning with Augmented Reality media and those who follow conventional learning. This study also aims to identify the effect of using Augmented Reality media on each aspect of critical thinking, such as the ability to analyze, make inferences, evaluate arguments, and explain logically. In addition, this study aims to describe students' experiences and perceptions of learning geometry based on interactive visual technology, so as to provide a comprehensive picture of the effectiveness and attractiveness of Augmented Reality media in the context of 21st-century learning.

The novelty of this research lies in integrating interactive visualization through AR into the geometry learning structure, which not only presents visual information but also facilitates higher-order thinking processes, such as analyzing spatial relationships, evaluating geometry arguments, and making inferences based on virtual objects that are directly manipulated by students. In this case, AR is positioned not just as a visualization aid, but as a cognitive stimulus to develop students' critical reasoning dimensions.

Thus, the main contribution of this research is to provide new empirical evidence regarding the effectiveness of AR media in developing students' critical thinking skills through visual and manipulative geometry learning, as well as presenting a learning model that is contextual, interactive, and follows the learning characteristics of 21st-century students.

METHOD

Research Approach and Design

This research uses a quantitative approach with a quasi-experimental method, which is complemented by qualitative data through observations and interviews. The experimental design used is Nonequivalent Control Group Design, which involves two groups of students, namely the experimental group and the control group, without random determination (Creswell, 2013). The experimental group received treatment in the form of geometry learning using Augmented Reality (AR) based media, while the control group followed learning without AR.

Quantitative data were obtained from critical thinking tests before and after treatment (pretest and posttest), while qualitative data were obtained through observations of the learning process and interviews with students and teachers to deepen understanding of the impact of AR media. The research design can be seen in the Figure 1.

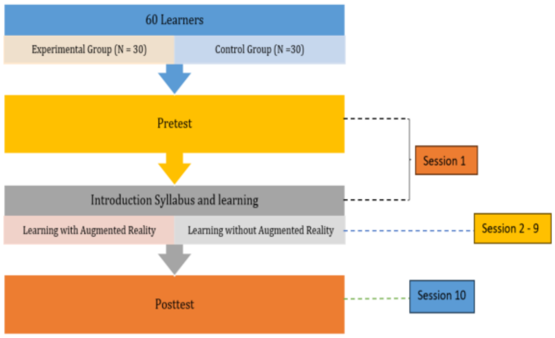

Figure 1. Research Design

Based on the Figure above, this research was carried out for ten face-to-face meetings with a duration of 2 x 40 minutes each, or 80 minutes per meeting. The whole process was carried out in a regular classroom with the support of technological devices (smartphones and AR applications) in the experimental group. The series of meetings is described as follows: The learning intervention was conducted over ten meetings, beginning with a pretest session, followed by the introduction of three-dimensional geometric shapes and their properties using Augmented Reality, continued with learning activities on geometric transformations (translation, rotation, and reflection), and concluding with problem-solving, reflection activities, posttest administration, and interviews.

Population and Sample

The population in this study was all grade VIII students in one of the public junior high schools in Banten Province in the even semester of the 2024/2025 academic year. The sample was taken by purposive sampling, taking into account the similarity of characteristics between classes, technology readiness, and teacher willingness. Two classes were selected as research samples: one class as the experimental group and one class as the control group, each totaling about 30 students.

Research Instruments

Critical Thinking Ability Test

This instrument was developed based on critical thinking indicators, namely: interpretation, analysis, evaluation, inference, and explanation. The test was in the form of geometry-based contextual description questions consisting of 10 items. Content validity was tested through expert judgment by three mathematics education lecturers, and reliability was tested using Cronbach's Alpha through an out-of-sample trial. Furthermore, the Normalized Gain (N-Gain) score was calculated to evaluate the improvement of students' critical thinking skills before and after treatment. The data were obtained from the results of the pretest and posttest, which were arranged based on critical thinking indicators, namely interpretation, analysis, evaluation, inference, and explanation. The calculation of N-Gain was done with the formula (Hake, 1998):

$$N - gain = \frac{S_{Post} - S_{Pre}}{S_{Max} - S_{Pre}}$$

The results of the N-Gain calculation are classified into three categories of improvement, namely high (N-Gain > 0.7), medium (0.3 ≤ N-Gain ≤ 0.7), and low (N-Gain < 0.3).

Observation Sheet

Observations were conducted during the learning process in both classes to record student activities, group interactions, and student engagement with the learning media. The observation sheet was descriptive and focused on learning activity indicators and critical thinking process indicators that emerged during learning.

Interview Guide

Interviews were conducted with 6 students (3 from the experimental group and 3 from the control group) and 1 math teacher. The interviews were semi-structured and aimed to explore perceptions of the learning process, students' cognitive engagement, and experience of using AR media.

RESULT AND DISCUSSION

Results

Table 2. Pretest and Posttest Results

Critical Thinking Indicator	Pretest Average (Experiment)	Average Pretest (Control)	Posttest Average (Experiment)	Average Posttest (Control)	Experiment N-Gain	N-Gain Control
Interpretation	45.2	44.7	82.5	61.3	0.68	0.3
Analysis	47	46.1	84.8	63	0.71	0.31
Inference	44.5	45.3	85.9	64.8	0.82	0.35
Evaluation	43.8	44	83.3	62.5	0.78	0.33
Explanation	42.7	43.9	80.5	60.7	0.74	0.31
Overall Average	44.6	44.8	83.4	62.5	0.75	0.32

This study involved two classes: an experimental class (using Augmented Reality/AR media) and a control class (using conventional learning). Critical thinking tests were conducted before and after treatment using validated instruments. The pretest and posttest result can be seen in Table 2.

Learning Observation Results

Observations were conducted for eight meetings in experimental and control classes using student and teacher learning activity observation instruments. The observation results are presented in the form of an average score on a scale of 1-4 for five indicators of learning activities. The average students activity observation score can be seen in Table 3.

Table 3. Average Students activity Observation Score

No.	Observation Indicator	Experiment Class	Control Class
1	Student participation in the discussion	3.8	2.5
2	Enthusiasm for using learning media	4	2.1
3	Ability to explain ideas verbally	3.6	2.3
4	Cooperation in solving problems	3.7	2.6
5	Effective use of study time	3.9	2.8
	Average Total Student Activity	**3.8**	**2.46**

Qualitatively, students in the experimental class showed active involvement in learning, seen from their initiative to discuss, try to rotate 3D objects through an Augmented Reality (AR) application, and explain to their friends. In contrast, students in the control class tended to be passive and only followed the teacher's instructions without independent exploration.

Observation records show that in the fourth meeting, two groups of experimental students compared the rotation of a space using AR devices. One student said, *"If you rotate it like this, the top side becomes the bottom, is that right?"*, which was then answered by another student while rotating the model directly. This kind of activity was not found in the control class.

Student and Teacher Interview Results

Interviews were conducted with five students from each class and one subject teacher to explore their experiences in the learning process. Students' perception scores were measured using a scale of 1-5. The average score of students' perception of learning can be seen in Table 4.

Table 4. Average Score of Students' Perception of Learning

Statement	Experiment Class	Control Class
I understand geometry concepts better	4.6	3.1
I enjoy learning with AR technology	4.9	-
I often discuss while studying	4.5	2.8
I am more confident in answering questions	4.4	3
Visualization helps me think more critically	4.7	3.2

The experimental class students' statements described a more meaningful learning experience. One student said, *"If it is only drawn, I am confused about which side to find. But if you can rotate it, I immediately know which side is the top, which side is the right side."* This expression shows that interactive visualization through AR media supports spatial understanding and encourages critical thinking. Students' critical thinking was reflected across all indicators, as they demonstrated the ability to interpret geometric information by identifying spatial elements, analyze relationships among geometric components, evaluate the accuracy of solution processes using visual evidence, infer logical conclusions from observed transformations, and explain their reasoning clearly by integrating verbal arguments with geometric representations, particularly in AR-assisted learning.

In contrast, students in the control class complained of difficulties in imagining geometric shapes only through two-dimensional images. One student stated, *"I memorized the formula, but I was confused about the shape. If asked why, the answer is like that, I'm not sure."*

The experimental class teacher considered that the use of AR media was very effective in increasing student motivation and interaction. He said, *"Students become more active in asking questions and discussing, sometimes even correcting each other. This is the first time I've seen this kind of learning spirit for geometry."*

In contrast, the control class teacher stated that most students looked confused and only followed the teacher's instructions passively. The teacher's instructions passively can be seen in Table 5.

Table 5. Teacher's Perception of Learning

Statement	Experiment (Score)	Control (Score)
Media supports students' concept understanding	5	3
Students are active and independent in learning	4.8	2.5
Students show improvement in critical thinking	4.6	2.9

Qualitative Analysis Based on Each Meeting

Qualitative descriptive analysis was conducted on the learning dynamics during the ten meetings. Student activities, interaction patterns, and learning outcomes were analyzed based on field notes, teacher reflections, and student performance progress. The qualitative analysis of the learning process reveals clear developments in students' critical thinking skills during instruction. As shown in Table 6, students in the AR-assisted class progressively demonstrated stronger abilities to interpret, analyze, infer, evaluate, and explain geometric

Table 6. Qualitative Analysis of Learning Process

Meeting	Activity	Quantitative & Qualitative Findings
1	Critical Thinking Ability Pretest	Average score <50 in both classes; students have difficulty answering inference and explanation questions.
2-3	Introduction to Spatial Buildings and Their Properties	87% of experimental students actively explored the AR model; control students only took notes without discussing.
4-5	Geometric Transformation (Translation)	90% of experimental students can practice translations with AR and explain the results; controls only 45% are able to explain verbally.
6-7	Geometric Transformation (Rotation)	High discussion in experimental class (score 3.9/4); control students were silent when asked the direction of rotation.
8-9	Problem Solving and Reflection	82% of experimental students solved the HOTS problem correctly; control students only 38% succeeded with logical reasoning.
10	Posttest and Interview	Mean posttest score of experimental class: 83; control: 62. Experimental students showed a sharp increase in the inference and evaluation indicators.

concepts through active exploration, discussion, and problem-solving activities, while such behaviors were less evident in the conventional class.

This part of the results shows that the use of Augmented Reality media in geometry learning significantly affects learning activities, student engagement, and their critical thinking skills.

Discussion

Interpretation

Interpretation is a basic critical thinking skill related to students' ability to understand and interpret information, including symbols, diagrams, images, and three-dimensional models in the context of geometry. In this study, students' interpretation skills in the experimental class significantly improved with an N-Gain of 0.68 (high category), while the control class only achieved 0.30 (moderate category). This indicates that the use of Augmented Reality (AR) as a learning medium plays a crucial role in helping students interpret geometric objects more accurately.

Observations revealed that students in the experimental class identified geometric shape elements such as edges, planes, vertices, and diagonals more quickly. When the teacher asked them to identify the qualities of a given form, they quickly modified the 3D model in the AR software by rotating, zooming in, or highlighting specific elements. This contrasted with the control class, which solely used static graphics on the board or in the textbook, and several pupils appeared to struggle recognizing aspects between identical geometric shapes. The teacher stated that augmented reality allowed students to "see" the relationships between geometric parts without requiring a high level of spatial imagination.

Interviews validated these conclusions. The majority of pupils in the experimental class reported that AR made it easier for them to understand geometric things because they could "observe real shapes" that they had previously only seen in two-dimensional representations. One student said: "Previously, I had to imagine a cube just from the picture in the book, but now I can rotate it myself and see all the sides, so it's easier to understand." The teacher also added that using AR reduced the time needed to explain three-dimensional shapes, freeing up class time for in-depth discussions and problem-solving exercises.

Theoretically, this improvement can be explained by (Huang et al., 2025), which states that information is more easily processed when presented in both visual and verbal formats. AR provides interactive visual stimuli that facilitate students' formation of strong spatial mental representations, while the teacher's explanations serve to reinforce conceptual understanding. This dual representation minimizes the misinterpretations that often arise in static image-based geometry lessons. AR significantly improves visual interpretation skills in subjects with high spatial content. (Rauschnabel et al., 2024) Also found that AR helped students bridge the gap between abstract representations (formulas and notation) and concrete forms, thus facilitating deeper initial understanding.

Furthermore, observations noted that experimental students frequently utilized AR as a discussion tool. They pointed out the geometric shapes in question and disputed conclusions based on the same augmented reality representation. This activity improved not only individual interpretations, but also group members' capacity to share consistent visual representations. This is consistent with the social constructivism viewpoint, which emphasizes that understanding is best acquired through social interaction using shared visual aids (Lin et al., 2023).

Interestingly, interviews found that pupils who previously had spatial challenges benefited the most. They reported feeling more confident in identifying geometric aspects since AR allowed for unfettered exploration without fear of inaccuracy. The teacher also mentioned that after viewing the AR model firsthand, these pupils are more likely to raise pertinent questions, such as comparing the differences in the spatial diagonals of a cube and a cuboid. Interview data indicate that students with low initial spatial ability benefited the most from AR-assisted learning. One student stated, *"Before using AR, I often felt confused and afraid of making mistakes, but with AR I can explore the shape freely and understand its parts more clearly."* A teacher also confirmed this improvement, noting, *"After observing the AR models directly, these students become more confident and start asking deeper questions, such as comparing the differences between edges, faces, or diagonals of geometric shapes."* This implies that excellent visual interpretation builds the groundwork for advanced critical thinking skills like analysis and evaluation.

A study by (F.-Y. Yang & Wang, 2023) backs this up, revealing that AR not only improves visual perception but also increases higher-order thinking skills through exploratory interactions. In the context of this study, competent interpretation serves as a starting point for conducting a thorough examination of the relationships between spatial elements, making logical deductions, and assessing more sophisticated mathematical techniques. Thus, the large improvement in interpretation indicators in the experimental class may be attributed directly to the AR-based interactive visualization, which integrates cognitive theory, social support, and exploratory activities. This implies that interpretation is not only a core talent, but also a necessary doorway to the development of a variety of other critical thinking skills in geometry learning.

Analysis

Analytical skills in geometry education include pupils' capacity to break down a subject or problem into smaller components, comprehend the links between elements, and rearrange them to answer increasingly complex problems. In this study, analytical skills improved significantly in the experimental class, with an N-Gain score of 0.71, considered high, as opposed to the control class, which only attained a score of 0.31, deemed moderate. This demonstrates that the usage of Augmented Reality (AR) has helped pupils study geometric elements with greater emphasis and depth.

Observations revealed that students in the experimental class actively used AR's interactive capabilities to visualize and break down three-dimensional things into simpler components. When studying prisms and pyramids, for example, students rotated virtual models to investigate the relationships between the base, height, and lateral planes, which were then linked to volume or surface area calculations. This practice contrasted with students in the control group, who were limited to two-dimensional representations in textbooks and frequently struggled to visualize spatial relationships between geometric parts. The teacher also observed that pupils in the experimental class were more likely to raise analytical questions, such as how volume varies when the base size is modified or how the diagonal of a room impacts surface area, showing more cognitive involvement.

Interview data corroborated these conclusions. Students stated that augmented reality visualization helped them better understand the links between geometric shape components. One student stated that rotating the object directly on the screen made it simpler to visualize how the base and height related to one another, avoiding the need to memorize the volume formula. The teacher also underlined that AR piqued students' interest and pushed them to perform their own analysis. According to the teacher, once passive students were now more involved in studying the relationships between elements and validating their comprehension by manipulating items in AR.

This gain in analytical skills is consistent with the ideas of Constructivist Learning Theory, which argues that understanding is developed through students' active participation in meaningful learning events. AR allows pupils to evaluate relationships between items directly, which strengthens their analytical skills. These findings are further reinforced by Spatial Visualization theory, which highlights the relevance of visual abilities in solving geometric issues. Three-dimensional visualizations created by AR improve students' spatial information processing, making it easier for them to correlate the features of geometric components. AR substantially improved students' spatial analysis by allowing them to interact with and control 3D models. (AlFadalat & Al-Azhari, 2022) AR also developed an exploration-based learning environment that helped students explore the links between mathematical components. AR was used not only as a visual assistance in this study, but also as a cognitive medium that facilitated analytical thinking processes through interactive, hands-on experiences.

Recent findings revealed that students with good analytical skills tended to reach logical conclusions more rapidly on the inference indicator and were better at rating the accuracy of answers on the assessment indicator. This shows that analysis is an important link between fundamental interpretation skills and higher-level critical thinking skills. Thus, AR substantially contributes to the development of analysis coupled with other critical thinking signs, making the geometry learning process not only procedural, but also reflective and based on deep comprehension.

Inference

Inference, or the ability to draw logical conclusions, is one of the most reliable indicators of critical thinking because it demonstrates students' ability to draw conclusions based on relevant evidence. Inference is important in geometry learning because it allows students to correlate visual input with mathematical principles and make logical conclusions about the subjects being studied. The results of this study show that students' inference skills in the experimental class greatly increased, with an N-Gain score of 0.82 (high category) compared to the control class, which only obtained 0.35 (moderate category).

Observations during the session revealed that students in the experimental class used Augmented Reality to validate their conclusions. For example, when learning geometric transformations like rotation or reflection, students used augmented reality to directly perceive the changes in object location. They then confirmed that the ensuing modifications corresponded to their previously projected conclusions. This task proved that their assumptions were no longer reliant on guessing, but rather on solid visual data provided by AR. Teachers remarked that this technique made classroom discussions more combative by allowing students to support their ideas with visual evidence that they could observe together.

According to interviews, pupils felt more secure in using augmented reality to reach conclusions. One student admitted, "I used to guess while answering questions regarding shadows or rotation. Now that I can see it directly on the computer, I am convinced that my conclusions are right." The teacher went on to say that the usage of AR enables pupils to compare their predictions with real-world visual results, allowing logical mistakes to be remedied immediately.

This phenomenon can be described theoretically using Inquiry-Based Learning theory, which emphasizes the relevance of evidence-based exploration in the development of critical thinking skills. AR allows students to directly test theories, examine logical repercussions, and refine their conclusions. Research by Oyman et al. (2022) found that AR helps students combine visual experiences with logical thinking, which strengthens inference skills.

Research by (Chang et al., 2022) found that AR provides a dynamic visual context, allowing students to conduct mental experiments using real-world visual representations. In the context of geometry instruction, this implies students not only imagine the implications of transformations or changes in shape, but also immediately see the visual evidence, resulting in more accurate and data-driven inferences.

The findings of this study also show that inference skills are highly tied to earlier indicators like interpretation and analysis. Good interpretation enables pupils to accurately understand the initial knowledge, whereas analysis enables them to break it down into logical components. AR improves both of these skills, giving pupils a solid basis for finishing. As a result, enhancing inference in the experimental class is not a one-time event, but rather the outcome of a collaboration between fundamental skills and AR-based learning experiences that enable evidence-based conclusion drawing. Thus, augmented reality serves as both a visual aid and a cognitive tool, allowing students to independently test hypotheses and verify conclusions. This makes geometry instruction more relevant and centered on critical thinking, rather than merely memorizing formulas.

Evaluation

Evaluation is a significant measure of critical thinking since it refers to students' capacity to appraise the validity of a process, argument, or mathematical solution using available information. In the context of geometry learning, this skill comprises verifying computation accuracy, evaluating the logic of solution stages, and comparing outcomes to appropriate visual representations or models. The results revealed that students' evaluation skills in the experimental class greatly improved, with an N-Gain score of 0.78 (high category), significantly better than the control class, which only scored 0.33 (moderate category).

Observations during the session revealed that students in the experimental class actively used augmented reality to evaluate their work. When solving issues requiring the volume or surface area of geometric objects, students utilized augmented reality to visualize the shapes, double-check the dimensions, and ensure that their calculations matched the visual form. Teachers observed that students rechecked solution steps more frequently before submitting their results, and they seemed to be able to recognize problems more rapidly when combining manual calculations with AR visualization.

Interviews with students confirmed these findings. A learner said: "If there's a discrepancy between my calculation results and the AR image, I immediately know there's something wrong with my calculation." The teacher also stated that AR helps pupils validate their responses since the visual evidence they see supports their grasp of right processes. In the control class, students had difficulties spotting faults without interactive visual assistance, thus the teacher had to provide more direct feedback.

In theory, this development in evaluative skills can be explained by the concept of metacognitive monitoring, which refers to the ability to monitor and manage one's own thought processes. Metacognitive monitoring is critical for detecting and correcting errors (Michalsky, 2024; Sutarto et al., 2022; Yassin, 2024). In this study, AR was used as an external tool to help with the monitoring process. When students noticed that the visual results in AR did not match their calculations, it initiated a reflection process that prompted them to reconsider the techniques or assumptions they were making. Research by (Avci & Kilic, 2024) found that interactive visual-based media, such as AR, can provide immediate feedback, which improves students' evaluative skills. This is also consistent with the self-regulated learning approach, which emphasizes the significance of learning tools that allow students to independently control and evaluate their learning process.

Observation data also show that group discussions in the experimental class were frequently focused on peer evaluation of answers. For example, when a student presented their answer via AR, their classmates used the visualization function to assess the appropriateness of the steps taken. This activity fostered a culture of mutual correction based on strong visual evidence, a practice rarely seen in the control class. Teachers noted that the quality of discussions improved because students relied not only on opinions but also on concrete visual representations to assess the validity of solutions.

Furthermore, teacher interviews revealed that students with moderate to low ability showed significant improvement in evaluation indicators because AR provided visual support that made it easier for them to understand where errors were. A teacher stated, "Students who are usually insecure are now more confident in checking their answers because they can directly compare them with the AR model." This suggests that AR helps narrow the gap between students with different initial abilities.

Good evaluation also leads to improvements in other indicators, such as explanation, where students who can assess the validity of solutions are more able to explain the reasoning behind the steps they use. In this study, improved evaluation became a catalyst for more reflective, evidence-based learning, so that students not only accepted the final answer as true, but also understood the underlying processes.

The literature supports these findings. (Chang et al., 2022) Research emphasizes that evaluation skills are crucial in technology-based mathematics education because they enable students to use interactive media as a tool for self-reflection. With AR, students not only solve problems but also engage in the process of evaluating the internal logic of each step of the solution. This prepares them for more independent and critical thinking-based learning at higher levels.

Overall, the improvement in evaluation skills in the experimental class indicates that AR not only helps students understand geometric concepts but also strengthens their ability to independently and evidence-basedly verify the correctness of solutions. This makes learning not only outcome-oriented but also a reflective process that encourages students to think critically and logically.

Explanation

Explanation is an indicator of critical thinking related to students' ability to communicate their understanding, thought processes, and the rationale behind their solutions clearly and logically. In the context of geometry learning, this skill includes the ability to explain calculation steps, the reasons for using certain formulas, and even justifying their considered correct solutions. This study showed that students' explanation skills in the experimental class significantly improved with an N-Gain of 0.74 (high category), while those in the control class only achieved 0.31 (medium category).

Learning observations revealed that the usage of Augmented Reality (AR) prompted students to become more interested in discussing their thought processes. Students in the experimental class were frequently prompted by the teacher to demonstrate their solutions using AR models as visual aids. For example, when teaching how to calculate the surface area of a prism, students not only wrote down the formula but also pointed to the appropriate parts of the prism in the augmented reality model. This made their answers more concrete and easier for their peers to follow, unlike in the control class, where explanations were mainly limited to writing on the board without interactive visual support.

According to the interview results, employing AR made it easier for students to explain their replies since they could offer visual evidence to back up their ideas. A pupil commented: "If I just explain it with words, it's sometimes hard to understand, but if I can show it directly in AR, my friends understand why I'm using that method." The teacher also noted that AR makes the presentation process more interesting and interactive, since other students can observe the same model while listening to the explanation of the problem-solving process.

Theoretically, this gain in explanation abilities is consistent with the concept of Cognitive Apprenticeship, which emphasizes the necessity of explicit visualization in articulating complicated thinking (Lange et al., 2021). AR serves as a cognitive tool, allowing pupils to express abstract ideas more concretely through clear visual representations. In the context of geometry learning, these visuals integrate verbal explanations with spatial evidence, thus increasing the clarity of students' arguments.

The scientific literature backs up these findings. According to AR facilitates explanation-based learning by providing a consistent visual framework for students to explain their reasoning. In a study by (Taub et al., 2024) found that augmented reality (AR) improved peer understanding during group conversations by facilitating the interaction of verbal explanations and visual evidence.

Classroom observations revealed that the usage of AR facilitated peer teaching. Students with a better grasp frequently used AR to assist struggling peers by altering models and highlighting crucial parts while describing how to solve problems. This not only improved the students' explanation skills, but it also helped the students hearing the explanations better understand the concepts through practical visuals. Teachers saw this phenomena as proof that AR fosters a collaborative learning environment that promotes richer academic discussion.

Interviews with teachers also suggested that pupils who had previously been passive in discussing their answers began to participate more actively. The teacher noted, "Students who were previously quiet are now more confidence in explaining because they feel assisted by AR. They are not scared to make mistakes because they can point straight to the subjects under discussion." This suggests that AR also boosts students' confidence in explaining their thought processes.

The quality of the students' arguments improved in tandem with their explanations. During class discussions, students in the experimental class were more likely to connect the stages they articulated with visual evidence from AR, such as pointing to specific sides or planes to support their reasoning for utilizing a formula. This is consistent with Xu et al.'s (2024) findings, which emphasize that explanation skills supported by interactive visualizations result in clearer, more structured, and more convincing mathematical communication.

Overall, AR improves explanation abilities by offering relevant visual material, allowing evidence-based communication, and giving students more confidence in presenting their reasoning. This technique not only helps students articulate solutions, but it also instills the academic habit of regularly supporting arguments with visible evidence. This research demonstrates that explanation skills are a key indicator that integrates all other components of critical thinking, from interpretation, analysis, inference, and evaluation, into a full logical thinking skill in AR-assisted geometry learning.

Implication

The outcomes of this study suggest that incorporating Augmented Reality (AR) into geometry education might considerably increase students' critical thinking skills by bridging the gap between abstract mathematical concepts and realistic visual representations. This study confirms AR's revolutionary potential as a cognitive tool that not only promotes conceptual knowledge but also stimulates higher-order thinking processes like analysis, inference, and assessment through interactive evidence-based learning experiences. For educators, these findings highlight the need of incorporating AR-based learning practices to build more engaging and student-centered classrooms in which students actively develop knowledge, validate their thinking, and successfully convey their ideas. More broadly, this study confirms the importance of AR in meeting the expectations of 21st-century education, which stresses digital literacy and inquiry-based problem solving. More research is needed to investigate the long-term impact of AR on other mathematical areas, its influence on various student demographics, and its potential when paired with other new teaching models.

Limitation

This study has various limitations that must be addressed before evaluating its findings. First, because the study only included pupils from one public junior high school in Banten Province, the results cannot be extrapolated to a larger population with diverse educational backgrounds, academic aptitude, and technological capabilities. Second, because the study focused solely on geometry, specifically geometric shapes and transformations, it is impossible to determine the impact of Augmented Reality (AR) on other mathematics topics or courses. Third, because the study was conducted over a very short period of 10 meetings, including a pretest and posttest, it is unable to describe the long-term impacts of AR on students' critical thinking skills. Furthermore, while the quasi-experimental approach paired with observations and interviews increased the data's validity, this study did not properly control for external variables such as variances in instructor AR skills and school technology infrastructure readiness. To get a more comprehensive knowledge of AR's effectiveness, more study is required, including a bigger and more varied sample, extending the duration of the intervention, and investigating its integration within a broader learning environment.

CONCLUSION

This study was conducted to examine the effectiveness of Augmented Reality (AR)–based geometry learning in improving junior high school students' critical thinking skills. The findings confirm that AR-assisted learning is more effective than conventional instruction, as indicated by a high overall N-Gain score in the experimental group (0.75) compared to only moderate improvement in the control group (0.32). Significant differences were found in all critical thinking indicators, where students learning with AR showed greater improvement in interpretation, analysis, inference, evaluation, and explanation than those in conventional classes. These results demonstrate that AR effectively supports active exploration, evidence-based reasoning, and meaningful engagement with geometric concepts, leading to higher levels of critical thinking compared to traditional geometry learning approaches.

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