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Integrating Augmented Reality in Mathematics Learning to Improve Critical Thinking Skills of Elementary School Students

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Abstract

This study aims to examine the effect of Augmented Reality (AR) technology-assisted learning on the critical thinking skills (CTS) of elementary school students in mathematics. A quantitative research approach was employed, using a post-test-only control group design involving 61 fifth-grade students with an average age of 11 years. The experimental group (n_1 = 31) received AR-assisted instruction, while the control group (n_2 = 30) received conventional teaching on the topic of spatial volume. Following a three-session intervention, data on students' CTS were collected through six descriptive test items, developed based on Facione's essential indicators of critical thinking. The instruments demonstrated content validity (0.736), face validity (0.645), and a reliability coefficient of 0.86. Data analysis included both descriptive statistics and inferential analysis using an independent samples t-test at a 5% significance level. The findings revealed a significant difference in CTS between students taught with AR-assisted learning and those taught using conventional methods, indicating that AR-supported instruction positively influences elementary students' critical thinking skills. However, two specific indicators—evaluation and inference—remained low across both groups. Therefore, future research should qualitatively explore these two dimensions to better understand how teachers can utilize AR technology to enhance students' evaluative and inferential thinking abilities.

Keywords:

Augmented Reality;

Critical Thinking;

Mathematics Learning;

Learning Technology.

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1- Introduction

Nowadays, critical thinking skills (CTS) have become an important discourse in the field of education and become the main goal of learning in a number of countries, such as Turkey, Malaysia, Vietnam, Singapore, and Indonesia [1-6]. At the same time, developing students' CTS remains a primary year-round homework for school mathematics teachers [7]. In Malaysia, for example, Ibrahim et al. [8] reported that fourth-grade students still have difficulties conjecturing, which is one of the key aspects of CTS because it involves students' mental processes in making predictions and problem-solving. A similar situation exists in Indonesia, where students still have relatively lower CTS than in Malay countries such as Malaysia and Singapore [6]. The development of critical thinking dimensions among primary school

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students in China is still unbalanced, and the scores of secondary students in the country have not met the standard essential thinking requirements set by the local curriculum [9]. This condition results in students being constrained to analyze situations, identify problems, and capture information and data to answer their various hypotheses during learning. This problem will continue outside the classroom, which may result in situations where students need to make better decisions when addressing problems repeatedly.

Critical thinking skills (CTS) are essential competencies that should be taught and practiced from the elementary school level [10], as they are among the key skills necessary for success in the 21st century [11–14]. These skills encompass the processes of interpretation, analysis, evaluation, inference, explanation, and self-regulation [15]. As a result, numerous researchers around the world have sought to promote CTS in school settings to help students thrive both now and in the future. Various studies have successfully enhanced students' CTS through a wide range of approaches, including STEAM-based blended learning methods [6, 16], peer interaction strategies [17], culture-based mathematics instruction [18, 19], problem-based model approaches (2022), problem-based learning models [10, 20–22], project-based learning [23], and the Socratic reflection approach [24]. Some researchers have even implemented more targeted strategies, such as using HOTS-based (Higher-Order Thinking Skills) science questions [25]. Despite these advancements, several studies still report that CTS among primary school students remains relatively underdeveloped [26–29], particularly in the area of evaluation skills [27]. In response to this, we aim to offer students a new learning experience by integrating augmented reality (AR) to support the development of their critical thinking skills, especially considering that the use of digital media is closely linked to the enhancement of CTS in elementary school students [29].

Research on the use of augmented reality (AR) in education has grown rapidly in recent years [30–32]. A systematic literature review by Ivan and Maat [33], based on data from Scopus and Web of Science, revealed a significant increase in the application of AR in mathematics education over the past five years (2019–2023), with Indonesian researchers contributing prominently to this trend. The integration of AR, which combines the physical world with digital elements to create new modes of learning and interaction [34], offers promising opportunities to enhance the quality of mathematics instruction. Empirical evidence has confirmed that incorporating AR into mathematics learning can foster spatial abilities [35, 36], positively influence cognitive and affective development [33], enhance critical thinking skills (CTS) [37], and improve students' overall learning outcomes [38]. Additionally, Demitriadou et al. [39] found in 2020 that the use of AR in elementary mathematics classrooms can increase student interactivity and interest in the subject. This finding underscores the idea that integrating AR technology with educational content can result in interactive applications that boost both the effectiveness and appeal of learning in real-life contexts [40]. The present study further affirms the value of AR integration in fostering engaging and high-quality mathematics learning experiences.

Previous research supports the view that developing aspects of CTS through AR is essential, as AR technology enhances geometry visualization [41, 42], provides interactive learning experiences [43], simplifies the identification of geometric objects from multiple perspectives [30], facilitates understanding of abstract concepts [39], and strengthens students' problem-solving skills [44, 45]. Despite the breadth of existing research on AR, the specific role of AR in improving the CTS of elementary school students remains underexplored. By leveraging technological advancements, students can use AR to explore virtual environments, manipulate digital content, and engage in hands-on, experiential learning activities that deepen their understanding [34]. This raises a critical question: Can these virtual experiences help elementary school students implement and evaluate problem-solving steps, draw logical conclusions, and make sound rational decisions in each learning situation? Therefore, the aim of this study is to analyze the effect of AR integration on mathematics-related critical thinking skills among elementary school students.

2- Literature Review

2-1- Critical Thinking Skills

Critical thinking is a general term that refers to the cognitive skills and intellectual dispositions that are effectively required to identify, analyze, evaluate arguments, and claim truth. According to Ennis [46], critical thinking is thinking that is reasonable and reflective and focuses on what to believe and what to do. Critical thinking is an important ability that every individual needs in life activities [7, 47]. Critical thinking is an ability that is effectively useful in the modern world because it increases students' chances of getting good academic results and enables them to solve complex real-life problems [48]. Studies show that individuals who have critical thinking skills can get the job done well [49-51]. CTS are not only important for individuals but are also needed on a macro scale. In the life of people in a country, a state system can only develop if people have critical thinking towards political, economic, and social issues [14, 52]. In addition, the importance of CTS is also reinforced by rapid technological changes and intense global economic competition, so critical thinking is believed to be one of the competencies needed by the younger generation to adapt to the times and to prepare themselves to enter the world of work [17, 53].

Facione [15] mentions that CTS consists of six main indicators, namely interpretation, analysis, evaluation, inference, and explanation. Interpretation is understanding and expressing the meaning of various kinds of experiences, situations, data, events, judgments, conventions, rules, beliefs, procedures, or criteria. Interpretation includes the sub-skills of categorization, deciphering meaning, and clarifying meaning. Analysis is the process of identifying actual relationships among statements, questions, concepts, descriptions, or other forms of representation intended to express beliefs, judgments, experiences, reasons, information, or opinions. Evaluation is the process of assessing the credibility of a statement, experience, situation, judgment, belief, or opinion. Evaluation also refers to the attempt to assess the strength of an inference, whether it is logical or not. Inference is the process of identifying and securing the elements necessary to design a reasonable conclusion. Thus, inference aims to form conjectures and hypotheses that are considered relevant to the information available and accompanied by strong evidence. Explanation is the ability of students to present solutions logically and convincingly. Explanation also refers to a person's ability to justify a reason accompanied by proof, conceptual, methodological, and consideration of valid logical criteria. Self-regulation is the ability of students to monitor and evaluate cognitive activities that have been carried out. Self-regulation aims to question, confirm, validate, or correct the work or problem solutions that have been presented.

Students with good CTS can develop reasoned and persuasive arguments and allow students to collect data from various sources relevant to a problem to be solved [54, 55] so that they can improve their quality of life in the future [56, 57]. It is possible because CTS possessed by individuals are important abilities to solve problems in a number of areas of life. It is also relevant to what Peter [58] said: students who have CTS will be responsive and efficient in solving problems and able to articulate information and their thoughts well. In the context of the 21st century, where individuals massively receive information from various sources, CTS are an important instrument that helps individuals articulate and interpret information. The most important thing is not the amount of information but how individuals can critically reason where the information comes from, what the content of the information is, why the information is important, and how the information can be converted into data in making decisions. That is why, in this era of information advancement, critical thinking is so important in determining one's life.

2-2- Augmented Reality

Augmented reality (AR) is a technology that incorporates virtual objects into natural environments [35, 59]. AR technology involves camera hardware such as AR glasses or smartphones to overlay digital content onto real-world objects so that users can view real and virtual environments simultaneously [60]. Learning using AR technology allows virtual elements to appear to coexist in the same time and space as natural environmental objects [61]. AR is a tool based on the technology of transferring factual external environments into digital devices and then processing them digitally by adding some effects and producing them through digital screens [62]. In general, AR is understood as a digital tool based on the unison between the real and virtual worlds that allows 3D virtual objects to be integrated with the real world [32]. In other words, the image presented by AR is an indirect view of the physical environment or real world that has been added to the virtual world through a computer or smartphone device [63] to facilitate the imagination and visualization of objects or materials so that it makes it easier for someone to understand in detail the structure of the object/material.

The ability of AR to provide a good three-dimensional visual experience is very promising to support the quality of learning [64, 65]. Lee [66] said that AR allows virtual information to be placed in the user's surrounding environment so as to enhance perception and interaction with the real world. In addition, AR is not limited to individual vision but also potentially to all senses. It will increase the information and perceptions perceived by individuals to be more real [67, 68]. For example, in the context of geometry learning, AR can help users understand abstract or complex concepts effectively [43]. It is possible because students who use AR can interact directly with abstract geometry objects [62]. When using AR, students can interact directly with geometry objects by zooming in, zooming out, rotating, and observing the entire geometry surface from all sides and angles. Students can be more optimal when analyzing or identifying complex geometric objects, comparing two different geometric objects, and performing simple simulations to understand the area or volume formula of a shape. Thus, the learning process with AR technology is more practical and aesthetic in observing objects, and it is easier to familiarize students with carrying out their critical reasoning.

2-3- Augmented Reality Determination on Students' Critical Thinking Skills

Sheehy et al. [69] explained that AR-based learning provides learners with the opportunity to learn and explore in a safe environment. Individuals can receive and process information directly and quickly, ensuring learning activities become more authentic, mediating community practices, and providing support for constructivist pedagogy. Furthermore, AR can develop users' thinking and visual abilities [36, 62]. We can see, for example, in the context of geometry learning, this ability is important to identify and analyze the properties of geometry objects in depth. It provides the fact that AR performance is needed in the process of analysis and interpretation, which is an important aspect that builds CTS. The conclusion is not excessive; at least, there has been empirical evidence that confirms the conclusion. For example, the findings of Pujiastuti et al. [70] successfully integrated AR into geometry learning to improve students' understanding of geometry concepts because AR presents complete and detailed information on an object scanned by an AR camera. Most recently, Hanggara et al. [71] proved that the integration of Augmented Reality-Based Mathematics Learning Games could improve problem-recognition skills, data collection and analysis, alternative assessment, and decision-making skills. It is because AR technology not only increases student involvement and interactivity but also strengthens the learning process.

The use of augmented reality (AR) in learning can help train students to think logically and systematically when solving problems [45, 72]. This aligns with Facione's view [73], which states that one of the key characteristics of critical thinking skills (CTS) is the ability to think logically when presenting solutions to problems. The integration of AR into mathematics education also has a significant impact on students' mathematical critical thinking levels (CTL) [71]. This finding is consistent with Hidajat's study [74], which suggests that AR can enhance mathematical communication skills, particularly those related to CTS indicators such as inference and explanation. Furthermore, AR supports the development of CTS through students' experiences in imagining and interpreting images or objects—commonly referred to as visual literacy, or the ability to derive meaning from visuals [75]. By presenting diverse visualizations of various geometric shapes and spaces, AR enables students to engage in interpretation, analysis, evaluation, inference, and explanation—core components for assessing one's critical thinking ability. This demonstrates that fostering students' critical thinking skills does not rely solely on problem-based learning models [10, 20, 21] or HOTS-based science questions [25], but can also be effectively achieved through the visual experiences provided by AR technology.

3- Method

3-1- Design and Procedure

This study used the post-test-only control group design research method. This design involves two groups, both of which are formed by random assignment. One group receives experimental treatment while the other does not, and then both groups are post-tested on the dependent variable [76]. Thus, both the experimental group (AR integration) and the control group will only be tested for CTS during the test, and the results of the two groups will be compared to see the difference. The AR application experimented with in this research is a type of mobile AR. Mobile AR uses a smartphone camera device as its primary device and uses images as triggers to display 3D digital content when the smartphone camera detects images [77].

The procedure of integrating AR through three learning subjects, with three meetings (see Figure 1). First, the subject is *"Identifying the properties of simple spatial shapes."* At the initial stage, the teacher provides a number of printed images in the form of flat and spatial objects, such as images of balls, drums, cardboard boxes, basketballs, wall clocks, and others. The images are then scanned using an AR application so that they can be displayed visually using a *smartphone*. The scanned images of objects are then fertilized into a form of space, namely the image of a drum into a tube, a picture of a rubric into a cube, a picture of a basketball into a ball, a picture of a cube into a block, and so on. Images of space and flat buildings that have been transformed/abstracted by AR applications are then analyzed for their properties, starting from the number of angles, number of sides, and number of ribs. At this stage, using the AR-transformed image is much better because it allows students to rotate, shift, and enlarge the image of the building so that students can freely analyze the properties of the building.

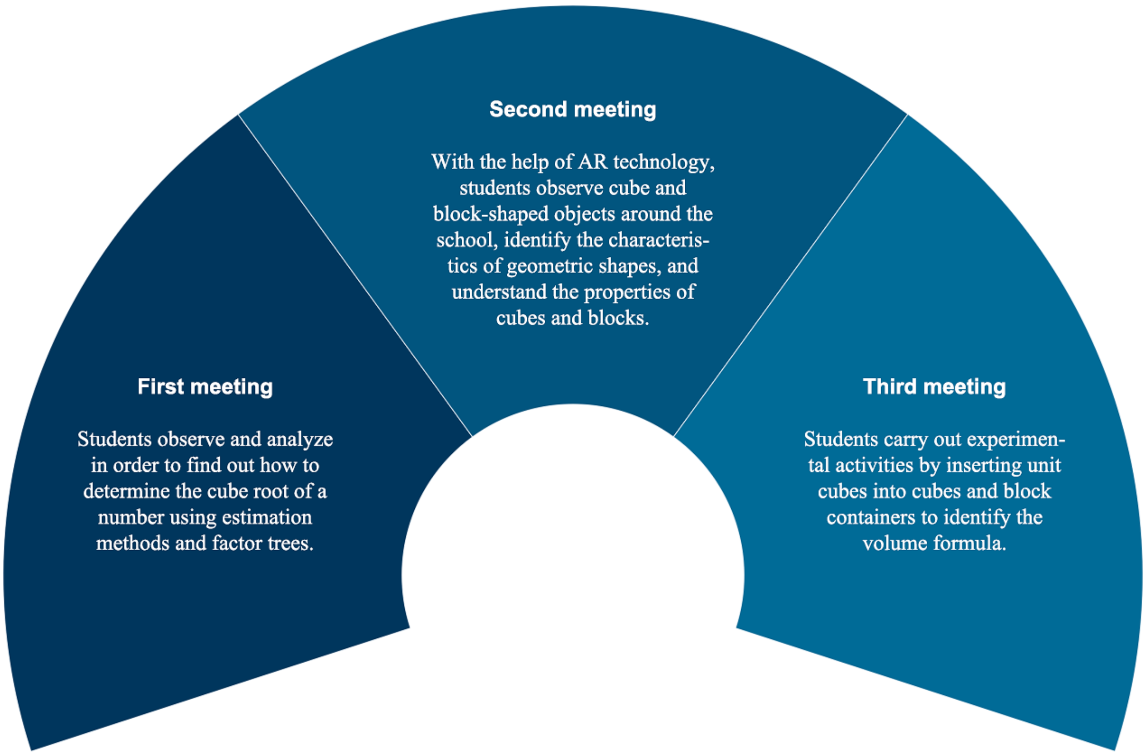

Figure 1. Student learning trajectory (3 meetings) of the experimental group

Second, the topic is *"Analyzing formulas to find the volume of cubes and blocks."* Students scanned cubic and cardboard block-shaped images to be presented by AR in turn. The images visualized by AR are then analyzed for differences, starting from the number of corner points, the number of students, and the size of the ribs on the cube and beam. The ultimate goal of this analysis is for students to know the differences and similarities between cubes and beams. It is the first step to knowing the formula to find the volume of cubes and beams. In the next stage, students use concrete objects in the form of containers and unit cubes to understand the volume of cubes and beams.

Finally, the subject *"Identifying the nets of cubes and blocks."* At this stage, students scan images of the cube (rubric) and block (cardboard) objects using AR. The images of cubes and blocks presented by AR are then converted into nets of cubes and blocks. The process of changing from cubes or blocks to nets can be observed in detail by students because AR presents the process of image movement accurately in the form of animation. At this stage, the nets of cubes and beams that the AR application can present we developed are only one image each. The other net images are used as material for student analysis without AR assistance. This step is used to train students' critical thinking.

3-2- Participant

We selected two groups of students through a cluster sampling technique: the experimental group ($n_1 = 31$), consisting of 17 girls and 14 boys, and the control group ($n_2 = 30$), composed of 18 girls and 12 boys. They ranged in age from 10 to 12 years old, and we also sought the consent of their teachers and parents before being assigned as participants. The participants came from diverse ethnic groups, namely the Bugis and the Makassarese, two major tribes that inhabit the province of South Sulawesi, Indonesia. The experimental group was given an intervention in AR technology-assisted mathematics learning, and the control group was given a conventional understanding of the learning model commonly used by teachers in the school. All students participating in this study were generally familiar with AR technology because they often use it in-game applications. However, they had never used AR directly in learning, so experimental bias could be minimized during the research process.

Before selecting the participants, we also collected data on students who took math courses outside of school so that their scores would not be included in the data processing process after the intervention. However, they still participated in the learning process with other participants. This method was also taken to ensure that students in the experimental and control groups only received mathematics learning from the intervention. Another reason is that this strategy was carried out because the research conducted was a type of pseudo-experiment, so it was not possible to create a new class. The experiment was conducted for three meetings, both in the experimental and control classes.

3-3- Instrument

The critical thinking test instrument was prepared in the form of a description and referred to the indicators of CTS from Facione [15]. Although Facione expressed six indicators of critical thinking, we only measured four main indicators, namely interpretation, analysis, evaluation, and inference. It was done due to several considerations, namely the limited time of the research as well as the explanation and self-regulation indicators that can only be known through a task-based interview process, so it will be difficult to do with elementary school students (see Table 1).

Table 1. Critical thinking skills assessment indicators

Indicator	Description
Interpretation	• Able to write down the known information in the test items • Able to write clearly and precisely about what is asked in the test items
Analysis	• Able to write the relationship of the concepts used in solving the test items
Evaluation	• Able to write the steps to solve test items • Able to evaluate each step taken
Inference	• Able to conclude the answer to the question logically
Explanation	• Able to provide reasons for the conclusions drawn.
Self-regulation	• Able to look back at the answers given/written down

Based on the CTS indicators presented in Table 1, ten descriptive questions were developed. These items were then thoroughly reviewed by five experts—two in educational research and evaluation, and three in mathematics education—to assess content validity and face validity. The feedback from these experts served as the basis for revising the formulation of each question. To further evaluate the instrument's validity and reliability, the ten items were piloted with 35 students from other schools within the same district as the research site, ensuring that the selected schools shared similar characteristics with the study sample. The results of the Q-Cochran test confirmed a content validity score of 0.736 and a face validity score of 0.645, indicating acceptable and consistent validity levels across the instrument (see Table 2).

Table 2. Results of the instrument validity uniformity test

Validity types	Significance value	Criteria
Content validity	0.736	Uniform validity
Face validity	0.645	Uniform validity

However, only six out of the ten developed items met the required validity standards. According to Guilford's criteria [78], item 1 achieved a validity coefficient of 0.817, placing it within the 0.80 < rxy ≤ 1.00 range, which indicates that it meets the criteria for being highly valid. Items 2 through 6 each fall within the 0.60 < rxy ≤ 0.80 range, indicating that they are valid (see Table 3). Specifically, items 1 and 2 assess the interpretation indicator; item 3 measures the analysis indicator; items 4 and 5 assess the evaluation indicator; and item 6 is designed to measure the inference indicator. The Cronbach's alpha value for the CTS instrument is 0.86, which falls within the 0.80 < rxy ≤ 1.00 range. This indicates that the instrument used to assess essential critical thinking skills is highly reliable and suitable for collecting data on elementary school students' CTS.

Table 3. Critical thinking skills instruments

No.	Questions	Score	Validity
1	A rubric's cube has a surface area of 216 cm^2. Determine the length of the edge of the rubric's cube!	0 1 2 3 4	0.817
2	A large cube is composed of 27 small cubes of the same size. If the length of the edge of each small cube is 5 cm, what is the volume of the large cube?	0 1 2 3 4	0.770
3	A cube has the same volume as a block. If the block has a length of 12 cm, a width of 8 cm, and a height of 18 cm. How long is the edge of the cube?	0 1 2 3 4	0.699
4	A cube-shaped aquarium has a depth of 30 cm. If 2/3 of the aquarium has been filled with water, how many liters of water must be added to make it completely filled?	0 1 2 3 4	0.646
5	A cube-shaped water reservoir without a lid with a depth of 2 meters will be fitted with ceramics. The ceramics to be installed are square with a side size of 20 cm. How many ceramics are needed to complete the work?	0 1 2 3 4	0.706
6	A fish farming pond is 15 meters long, 2 meters wide, and 1 meter deep. Due to insufficient capacity, the pond owner renovated the pond by increasing its depth. How much depth must be added so that the pond can hold 45m^3 of water?	0 1 2 3 4	0.782

Furthermore, to facilitate the scoring of students' CTS, the researcher modified the scoring rubric (scoring guidelines) for critical thinking indicators developed by Facione [73] using five graded scales with scores of 0-4, as presented in Table 4.

Table 4. Rubric for assessing students' critical thinking skills

Indicator	Students' response	Score
Interpretation	• Does not provide an answer or gives an incorrect answer, or the response is completely incomprehensible.	0
	• Able to identify information from the given problem, but unable to select the important information and does not provide problem-solving steps.	1
	• Able to identify important information from the given problem, provides problem-solving steps but only a small portion.	2
	• Able to identify important information from the given problem, provides most of the problem-solving steps, but the steps are not systematic, or errors occur in the calculation process.	3
	• The calculation process is correct, the problem-solving steps are correct, and the final result is correct.	4
Analysis	• Does not answer or does not provide an idea relevant to the problem.	0
	• Able to identify information from the given problem, but unable to select the important information.	1
	• Analyzes the missing information in the problem and elaborates on additional information for problem-solving.	2
	• Provides a relevant solution, but the problem-solving steps are incomplete, or the calculation is incorrect.	3
	• Produces a relevant solution for problem-solving and writes it clearly and comprehensively.	4
Evaluation	• Does not provide an answer or gives an incorrect answer, or the response is completely incomprehensible.	0
	• Presents additional information not provided in the problem, but it is incomplete or contains minor errors.	1
	• Presents additional information not provided in the problem comprehensively and systematically.	2
	• Writes problem-solving steps but they are incomplete or contain calculation errors or minor mistakes.	3
	• Writes problem-solving steps systematically, comprehensively, and correctly.	4
Inference	• Does not provide a solution or provides an incorrect and illogical solution.	0
	• There is an inaccuracy in developing a strategy without detailing it.	1
	• There is an inaccuracy in developing a strategy, and it is accompanied by a lack of detailed explanation.	2
	• Develop a strategy accurately with the correct problem-solving steps, but it is incomplete.	3
	• Develop a strategy accurately and comprehensively.	4

3-4- Data Analysis

The CTS post-test data were analyzed using both descriptive and inferential statistics through an independent samples t-test with a significance level of 5%. The normality of the data in both the control and experimental groups was assessed using the Shapiro-Wilk test, while the homogeneity of variance was tested using Levene's formula. The basis for the first hypothesis test is as follows: if the significance value (2-tailed) is less than 0.05, there is a statistically significant difference in CTS between students who received AR-assisted learning and those who received conventional instruction. Conversely, if the significance value (2-tailed) is greater than 0.05, there is no significant difference in CTS between the two groups. All statistical analyses were conducted using IBM SPSS Statistics version 25.

4- Results and Discussion

4-1- Results

Respondents' answers to the six research questions were then scored according to the assessment rubric (see Table 4). As a result, respondents' answers with a score of 0 were only found in question item number 6 (inference indicator) in the control group, which was 2.2%. Furthermore, at a score of 1 for questions number 1 to four (interpretation, analysis, and evaluation indicators), there was no distribution of student data from the two research groups. On the other hand, in item 5 (evaluation indicator), two students got a score of 1 from both research groups. In contrast, in item number 6 (inference indicator), the control group had a higher score frequency, which was 7 (23.3%), 13.6% higher than the experimental group. Continuing to score 2, all CTS question the control group dominated items; only in item 6 (inference indicator) the experimental group was 8.1% higher (gain = 3; 17> 14) than the control group. In other data, not a single respondent was found to have a score of 2 on questions 1, 2, and 3 (0%).

For score 3, the experimental group is higher in three question items: the third, fourth, and sixth. At the same time, the other three items are outperformed by the control group, namely the first and second items. For the fifth item, both groups each shared 12 respondents; however, the control group had a higher presentation (40.0%) because it had a smaller sample size (30 respondents) than the control group (31 respondents). The highest score, namely score 4, is dominated by the control group in all question items (all indicators of CTS). The most significant gain is in the second item (21.2%), followed by the first item (17.5%), where both items are interpretation indicators. At the same time, the lowest gain is in the sixth item (inference indicator), which is 3.2% (see Table 5). This fact has underlined that although the integration of AR in learning has a positive impact on improving students' CTS, two important indicators, namely evaluation and inference, need to be highlighted in the student learning experience when teachers orchestrate their teaching to enhance students' experience in optimizing their critical thinking through AR integration.

Table 5. Description of students' critical thinking skills scores

Question	Students' critical thinking skills scores									
	0		1		2		3		4	
	Experim.	Control	Experim.	Control	Experim.	Control	Experim.	Control	Experim.	Control
Item 1	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (3.3%)	8 (25.8%)	12 (40.0%)	23 (74.2%)	17 (56.7%)
Item 2	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	11 (35.5%)	17 (56.7%)	20 (64.5)	13 (43.3%)
Item 3	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	5 (16.7%)	20 (64.5)	19 (63.3%)	11 (35.5%)	6 (20.0%)
Item 4	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	3 (9.7%)	10 (33.3%)	18 (58.1%)	14 (46.7%)	10 (32.3%)	6 (20.0%)
Item 5	0 (0.0%)	0 (0.0%)	2 (6.5%)	2 (6.7%)	12 (38.7%)	15 (50.0%)	12 (38.7%)	12 (40.0%	5 (16.1%)	1 (3.3%)
Item 6	0 (0.0%)	1 (2.2%)	3 (9.7%)	7 (23.3%)	17 (54.8%)	14 (46.7%)	9 (29.0%)	7 (23.3%)	2 (6.5%)	1 (3.3%)

Note: First row frequency; second row percentage.

The student's CTS scores were then converted to a range of 100 using the formula of student scores divided by maximum scores multiplied by 100 [79]. The average value of students' CTS in the experimental class was 78.90. This figure is greater than the average value of students' CTS in the control class, which was only 71.94. The experimental class's highest CTS score was 95.83, while the control class's highest CTS score was 91.66. The experimental class's lowest CTS score was 62.50, while in the control class, it was 54.17. The standard deviation value in the experimental class was 10.43, and the control class was 11.26. The acquisition of CTS scores in mathematics in the experimental and control classes based on each question item can be seen in Table 6.

Table 6. Mean and standard deviation of students' thinking skills

Question	Mean		Standard deviation	
	Experimental	Control	Experimental	Control
Item 1	15.59	14.72	1.85	2.37
Item 2	15.18	14.30	2.02	2.09
Item 3	13.98	12.64	2.02	2.56
Item 4	13.44	11.94	2.56	3.04
Item 5	10.99	9.97	3.55	2.87
Item 6	9.63	8.22	3.19	3.76

Table 6 shows that the average student score for item 1 is the highest among all items, indicating that students performed best on the interpretation indicator. This trend is observed in both the control and experimental groups. In contrast, item 6 has the lowest average score in both groups, suggesting that students' CTS in mathematics related to the inference indicator remain relatively low compared to other indicators.

These findings are further supported when analyzed by indicator. The largest improvement is seen in the inference indicator, with a gain of 1.41, followed by the analysis indicator with a gain of 1.34, the evaluation indicator also with a gain of 1.34, and finally the interpretation indicator, which shows the smallest gain at 0.87 (see Figure 2). This implies that, overall, the average scores in the experimental group exceed those in the control group across all items and indicators.

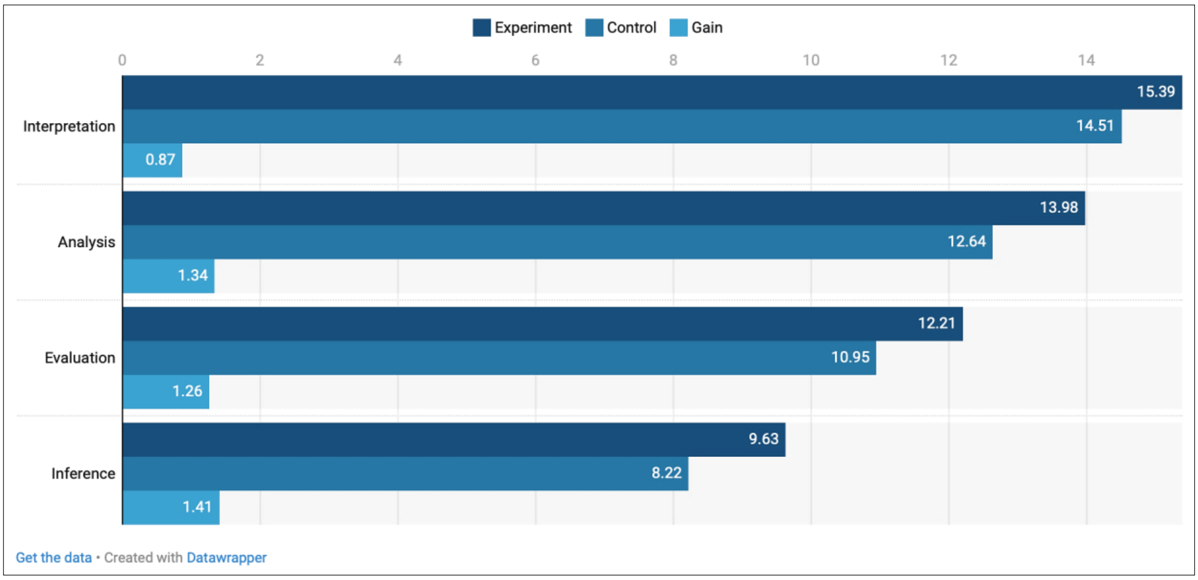

Figure 2. Differences in critical thinking indicators of students in the experimental and control groups

The results of the categorization of CTS scores of students in the experimental and control groups are presented in Table 7. In addition, the distribution of the number of students based on the categories that have been set is shown. The number of students in the experimental class whose scores are in the medium category is 10 (32.25%), and the number of control classes in the medium category is 18 (60%). Meanwhile, the number of students in the experimental class whose scores are in the high category is 16 (51.61%) and in the control class is 11 students (36.66%). Furthermore, as many as 5 students (16.12%) from the experimental class obtained scores in the very high category, while from the control class, only 1 person (3.33%).

Table 7. Categorization of students' thinking skills in the experimental and control groups

Score	Category	Frequency		Percentage (%)	
		Experimental	Control	Experimental	Control
0 - 39	Very low	0	0	0%	0%
40 - 54	Low	0	0	0%	0%
55 - 74	Currently	10	18	32.25%	60%
75 - 89	High	16	11	51.61%	36.66%
90 - 100	Very high	5	1	16.12%	3.33%

The Shapiro-Wilk normality test data is called regular if sig. > 0.05. Referring to Table 7, the significance value in the AR-assisted learning design learning dataset is 0.073 > 0.05, so it can be concluded that the data is usually distributed. Furthermore, the significance value in the control class is 0.065 > 0.05, so it can be concluded that the data is also normally distributed. Levene's homogeneity test results are said to be homogeneous if the significance value is more significant than 0.05. The results of Levene's test obtained a significance value of 0.576 > 0.05 (see Table 8), which means that the variation of the research data of the two groups is homogeneous.

Table 8. Results of normality and homogeneity tests

Group	Sig. (Shapiro-Wilk)	Sig. (Levene statistic)
Experiment	0.073	0.576
Control	0.065	

Based on the independent samples t-test table (see Table 9), the sig. (2-tailed) value is 0.015 or less than 0.05. It means there is a significant difference in critical mathematical thinking skills between students who receive AR-assisted learning and those who receive conventional learning.

Table 9. Independent samples t-test

	t	df	Sig. (2-tailed)	Mean differences
t-test for equality of means	-2.503	59	0.015	6.953

4-2- Discussion

The statistical results of this study indicate that augmented reality (AR) can serve as an effective alternative technology to be integrated into mathematics education—particularly in teaching spatial volume—due to its proven ability to enhance elementary students' critical thinking skills (CTS). This finding aligns with the results of previous research by AlNajdi (2022) [80], which examined the effectiveness of AR in learning environments. AlNajdi's study [81] found that the use of AR in the classroom fosters greater inclusivity in student engagement and improves performance across various subjects and contexts. Similarly, this finding is consistent with the exploratory research of Cahyono et al. (2020) [81], which emphasized the role of AR in bridging real-world experiences and abstract mathematical concepts. In practice, incorporating AR into classroom activities—particularly in teaching spatial geometry—enhances students' geometric visualization skills, enabling them to identify geometric objects from multiple perspectives more easily [41, 82]. As a result, students are better able to grasp the geometric concepts being taught [39].

The findings of this study further confirm that AR effectively promotes student exploration [36, 41], enhances their abilities to analyze and interpret information [83], develops their problem-solving skills [45], and facilitates understanding of mathematical content such as geometry [84], ultimately leading to improved learning outcomes in mathematics [85, 86]. AR technology contributes to students' CTS by fostering visual literacy experiences. Through the use of smartphone cameras and AR applications that display 3D digital content, students' imagination is stimulated [75, 77]. Visualizations of spatial and flat shapes presented via AR help students analyze key features such as the number of angles, sides, and edges. The dynamic and interactive nature of AR—allowing students to rotate, slide, and zoom in on geometric figures—supports deeper critical engagement with the properties of these shapes.

Moreover, students are able to compare and contrast geometric characteristics, including the number of vertices, edges, and faces of cubes and rectangular prisms, thus enabling them to critically distinguish similarities and differences. Additionally, AR allows students to convert 3D objects into their corresponding nets, providing an animated and accurate representation that enhances their ability to observe, analyze, and understand geometric forms in a more comprehensive manner.

When looking at the thought process of AR integration in the student learning experience above, it is certainly different when compared to the research of Elsayed & Al-Najrani [59] and the research of Nadzeri et al. [87], because their study only explores the impact of AR on visual and spatial intelligence. AR technology is very likely to promote higher-order thinking skills such as CTS. Therefore, the findings of this study complement and enrich previous research, where AR, in addition to fostering spatial ability [35, 36], has also been shown to improve problem-solving ability [44, 45]. AR technology has demonstrated the capacity to stimulate students to think about a wide variety of scientific ideas, fostering deeper connections between scientific concepts and encouraging students to have a more active learning style with improved transitions between inquiry activities [88]. Our research findings indicate that AR can effectively improve critical thinking skills (CTS) in mathematics. Additionally, this study also adds insight. It confirms previous research that students' mathematical CTS can be enhanced from elementary school age because elementary school students can think about particular objects in a complex way and also take into account the importance of developing CTS early on [89, 90].

This research intervention differs from the approach taken by Kim et al. [37], who used robotic coding in learning geometry space. The success of Kim et al. [37] is determined by teachers' ability in the classroom, given the relatively tricky process of operating robotic coding, especially for use in low-grade students. It is relevant to the recent findings of Mahmud & Mustafa Bakri [91], who concluded that some of the challenges of using robotic coding are programming difficulties, so students must be equipped with robot programming materials. This is undoubtedly the best comparison with AR technology, which offers ease of operation and development [43]. It is a learning medium that significantly facilitates learning and can change students' thinking. In addition, by using AR technology in learning, teachers can facilitate the exchange of information with their students [92], allowing students to visualize and interact with what is taught in class to increase student interest, motivation, and science process skills [93, 94].

As an essential skill to support students' life success in the 21st century, CTS should be a necessary part of primary school students' learning [10-13]. That means teachers are responsible for exploring models, media, learning materials, and other supporting tools that stimulate students so that they can understand various information and data meaningfully, are able to differentiate, organize, and attribute information to become essential data in making conclusions, are able to verify multiple information and data logically, objectively, and credibly, and are able to diagnose a necessary element of information and data to provide methodological and accountable problem-solving solutions [15, 95, 96]. The critical thinking process that students have learned and developed from elementary school helps them to grow and develop into individuals who more selectively manage their thoughts before making decisions. They also quickly sort out various thoughts and behaviors that are irrelevant to the needs of self-development in academic and non-academic environments. Suppose this condition continues to develop in a positive direction. In that case, student learning activities at the junior high school level to college will be more autonomous and also active and productive so that heutagogical learning behavior becomes a pleasant learning experience for students while continuing to encourage the growth of innovations in solving learning problems and solving problems in students' daily lives.

Long before that, the determination of CTS in life has been recognized since classical Greek times. It has been considered an essential skill since both Stanic et al. [97] and Taghinezhad & Riasati [98]. Bloom then modified this concept in the 1950s. This skill became popular in the 1990s [98] and placed CTS as one of the higher-level thinking skills [95, 99] in a person's thinking taxonomy, which was then widely adopted in measuring student learning outcomes in various parts of the world. Studies and analysis related to critical thinking formally in education were first carried out by Bugg & Dewey [100] using the term reflective thinking. Reflective thinking occurs when individuals are in a state of "confusion" so that they are encouraged to formulate guesses or suggestions on how to solve problems. Until now and in the future, the importance of CTS is still considered a mandatory ability for contemporary society. The world needs individuals with CTS to face the increasingly complex challenges of life, especially with the proliferation of information and data. Ultimately, individuals will need clarification if the information and data cannot be used critically before making decisions. Eventually, they will be trapped in a routine activity without a clear goal. Practically speaking, CTS is also needed to get a job in the global economy, maintain a democratic lifestyle, and make decisions in a rapidly changing society [14, 98].

Once again, the demands of a massive transformation from an agrarian society to an industrial society and a society of knowledge introduced by Richard D. Crawford as the Era of Human Capital [101] make CTL crucial. A nation's future progress is no longer determined by the natural wealth owned by the country. Still, it is primarily determined by the extent to which its people master science and good CTS. This conclusion has also been predicted by O'Neill [102] and Hanzlová & Kudrnáč [103] long before. They projected that in the 21st century, there would be a process of technological integration in human life, rapid acceleration of information flows, changes in economic patterns, and leaps in global industrial growth so that people must be equipped with CTS to adapt to complex times so that they do not experience surprises and difficulties in the future. Schools are a place to prepare students' lives for the future, so they must be able to design various student learning experiences relevant to the times' needs and developments so that students do not become victims of advances in science and technology. It includes supporting the development of teacher competencies to make learning approaches, methods, and strategies effective and efficient with their expertise, personality, and social relations to explore students' potential [104].

Therefore, this study noted some constraints for future studies, such as the relatively small sample size. Hence, the results need to be carefully generalized to a broader demographic. In addition to the six components of CTS, we only studied four indicators: interpretation, analysis, evaluation, and inference. Therefore, we suggest that future research study how AR technology can affect CTS regarding explanation and self-regulation. Of course, it will be complete if the quantitative data is complemented by other qualitative studies (explanatory sequential design). In terms of time, we only used AR for three meetings in math class, so we suspect that using AR with a higher frequency will encourage improving CTS in all aspects, including evaluation and inference indicators. Another path that can be taken to improve future performance is to design AR applications that have an attractive appearance so that students can be more accessible and not get bored when doing exploration activities, especially elementary school children who still like things that are visualized so that they can encourage their critical exploration experiences.

5- Conclusion

This study provides one empirical fact: the advancement of AR technology must become an integrated learning experience in every topic of discussion among teachers in class. AR technology in mathematics learning can improve the CTS of elementary school students by combining virtual objects and actual conditions. The average value of students who integrate AR technology in mathematics is higher than the CTS in mathematics of students in conventional classes that do not use AR. In the trial on three discussion topics, the independent samples t-test analysis also showed a significant difference in CTS ($\alpha = 0.05$) between students who used AR and students who did not use AR in learning. Based on the CTS indicators, the highest difference was recorded in the inference indicator with a gain of 1.41, the analysis indicator with a gain of 1.34, and the evaluation indicator with a gain of 1.34. Therefore, the interpretation indicator only had a gain of 0.87.

The above data has highlighted that although AR integration has positive implications for improving elementary school students' CTS, two important indicators, namely evaluation and inference, need further discussion by teachers when integrating AR into students' learning experiences. In addition, the limitation of this study is that it uses a limited sample, so a more comprehensive sample demographic modification is needed to improve future work. AR technology is likely to be applied to other subjects outside of mathematics learning, so research is required to determine AR technology's effectiveness on different skills (besides CTS) that support students' 21st-century learning and life. Remember to explore teachers' competence in AR technology, especially in disadvantaged areas. Technological advances and student thinking progress are also greatly influenced by teacher competence in integrating technology and orchestrating student performance tasks through selected learning models and methods.

6- Declarations

6-1- Author Contributions

Conceptualization, A.A., M., and A.; methodology, A.A. and J.B.; software, M. and E.D.P.; validation, T.H. and D.S.; formal analysis, A.A. and E.D.P.; investigation, T.H., D.S., and J.B.; resources, A.A., M., and A.; data curation, M., A., and E.D.P.; writing—original draft preparation, A.A.; writing—review and editing, T.H. and D.S.; visualization, A.A. and J.B.; supervision, T.H. and D.S.; project administration, A.A., M., A., and E.D.P.; funding acquisition, A.A., M., A., and E.D.P. All authors have read and agreed to the published version of the manuscript.

6-2- Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6-3- Funding

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6-5- Institutional Review Board Statement

Not applicable.

6-6- Informed Consent Statement

Not applicable.

6-7- Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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