

Improving Mathematical Creativity: The Utilization of Augmented Reality for Elementary Students' Learning

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Abstract

Creative thinking is an essential skill that elementary school students must possess to face the challenges of the 21st century. The purpose of this study is to analyze the impact of improving and achieving students' mathematical creative thinking abilities through the intervention of Augmented Reality (AR)-based learning. Two groups of students were involved: an experimental group that received AR-based learning and a control group that underwent conventional learning. The aspects of creative thinking abilities measured included fluency, flexibility, elaboration, and originality. These aspects were evaluated through pre-tests and post-tests. A total of 62 students participated in this study, consisting of 32 students in the experimental group and 30 students in the control group. Data were collected using essay tests designed to measure students' creative thinking abilities. The results of the mean difference test showed that the experimental group achieved significant improvement in creative thinking abilities compared to the control group. AR proved effective in enhancing student engagement and mathematical creative thinking abilities, particularly in the aspects of fluency and flexibility. This study recommends the use of AR as an innovative tool for mathematics learning in elementary schools.

Keywords: Mathematical creativity, Augmented reality, Elementary school.

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1. Introduction

Creative thinking is an essential skill that students need to master in order to adapt to the complexities of globalization (Astuti et al., 2019). It facilitates not only innovative approaches to problem-solving but also serves as a cornerstone for cultivating higher-order thinking abilities (Akbar et al., 2023). In the field of mathematics education, creative thinking holds significant importance because mathematics is often viewed as a subject that emphasizes logical reasoning and analytical processes. Guilford (1967) highlights that creative thinking encompasses the ability to produce new ideas, adapt thinking flexibly, expand on concepts in detail, and devise original solutions. As such, integrating creative thinking into mathematics instruction can play a pivotal role in preparing students to meet the evolving skill requirements of the 21st century (Hassoubah, 2004).

However, several studies show that elementary school students' creative thinking abilities are still at a low level. This is caused by the dominance of conventional learning methods which are teacher-centered so that they provide less space for students to explore their creative thinking (Adharini & Herman, 2021). In addition, the majority of mathematics learning in elementary

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schools tends to emphasize procedural problem solving without much exploration of concepts that can stimulate student creativity (Sutoyo & Priantari, 2019). As a result, students tend to be passive and focus more on memorization than on in-depth understanding of the material being studied. This monotonous learning model also reduces students' motivation to participate actively in the learning process, making it difficult for creative thinking skills to develop optimally.

To overcome this challenge, a more innovative learning approach is needed that involves active student interaction in the learning process (Bahari et al., 2018). One approach that is receiving increasing attention is the use of Augmented Reality (AR) technology in learning (Yamtinah et al., 2023). AR is a technology that combines virtual elements with the real world, creating a more interesting and interactive learning experience. In the context of mathematics learning, AR can help visualize abstract concepts, such as geometry, algebra, and graphics, to become more concrete and easy to understand (Koparan et al., 2023). According to Pujiastuti et al. (2020), the use of AR in the learning process can increase student motivation, enrich the learning experience, and make it easier for students to understand complex concepts. Through this technology, students not only learn through text or images but can also interact directly with learning material in the form of interesting visual simulations.

Various studies have postulated the possibilities of AR technology in developing students' creative thinking abilities. Research by Hakim et al., (2024) shows that the application of AR in mathematics learning can improve students' abilities in divergent thinking, one of the main components of creative thinking. Additionally, a study by Chen, (2019) revealed that AR helps students generate creative solutions by visualizing relationships between concepts more dynamically. Furthermore, İslim et al. (2024) reported that AR-based learning media was able to improve students' creative thinking abilities in solving geometric problems. These studies highlight that AR technology has great potential to develop various aspects of creative thinking, such as fluency, flexibility, elaboration, and originality.

Apart from honing creative thinking skills, AR technology also offers several other benefits in learning, including increasing student engagement and making it easier for teachers to explain difficult concepts. Xiong et al. (2021) explain that AR provides students with the opportunity to learn through hands-on experiences that not only strengthen their understanding of concepts but also help them develop creative ideas independently. In mathematics learning, AR can create a learning environment that allows students to experiment with various approaches to solving problems without fear of making mistakes (Dinayusadewi & Agustika, 2020). This is in line with (Brousseau (1997) didactic situation theory which emphasizes the importance of experience-based learning in developing higher-order thinking abilities. Furthermore, the use of AR can create a more enjoyable learning atmosphere and ultimately increase students' motivation to learn actively (Estapa & Nadolny, 2015).

Even though AR technology has many advantages, its application in elementary schools still faces several challenges. One of the biggest challenges is the availability of devices and infrastructure that support the use of AR (Elsayed & Al-Najrani, 2021). Dinayusadewi and Agustika (2020) revealed that many schools in Indonesia still have difficulty providing technological devices, such as tablets or smartphones, which are needed to implement AR-based learning. In the context of basic education in Indonesia, it is important to conduct a more in-depth study of how AR technology can be applied effectively to improve students' creative thinking abilities.

This research aims to analyze the effect of applying Augmented Reality technology on the development of students' creative thinking abilities in mathematics learning. This research will focus on four main aspects of creative thinking, namely fluency, flexibility, elaboration, and originality. Thus, it is hoped that the results of this research can provide relevant

recommendations for optimizing the use of AR in mathematics learning. The ability to think creatively is one of the main skills that must be developed in learning mathematics in elementary schools. However, the low level of this ability among students indicates the need for more innovative and relevant learning approaches. Augmented Reality technology offers a promising solution to improve students' creative thinking abilities through a more interactive and immersive learning experience. Apart from providing benefits in honing aspects of creative thinking, AR also creates an interesting and fun learning environment for students. It is hoped that this research can make a significant contribution to the development of technology-based learning theory and practice, as well as offer practical recommendations for improving the quality of basic education.

2. Method

This research employed a quasi-experimental design. The researchers did not create artificial or specific groups for the sample but instead used intact groups from existing classes in the school. This approach was chosen to ensure that the school's learning process remained undisrupted. The research design followed a pretest-posttest control group format. A total of 62 students participated in the study, divided into two groups: 32 students in the experimental class and 30 students in the control class. The experimental group received intervention in the form of AR-assisted mathematics learning, while the control group engaged in conventional learning.

The instrument used in this study was a creative thinking ability test. This instrument consisted of four questions designed based on the aspects of creative thinking abilities proposed by Torrance (1966), which include fluency, flexibility, elaboration, and originality. The test was administered in two stages: the pretest was conducted before the intervention, and the posttest was conducted after the intervention. The scoring criteria for the mathematical creative thinking ability test were adapted from the mathematical creative thinking ability scoring rubric developed by (Bosch, 1997), as detailed below.

Table 1. Guide to Scoring Creative Thinking Abilities

Indicator	Student Response	Score
Originality	Does not provide an answer or provides an incorrect one.	0
	Write an answer that is difficult or impossible to understand.	1
	Write an answer with a directed calculation process but incomplete or incorrect.	2
	Provides a solution with a specific strategy but is inaccurate or miscalculates.	3
	Both the calculation process and results are correct.	4
Fluency	Does not respond or provide ideas relevant to the problem.	0
	Produces a relevant solution to the problem but with unclear writing.	1
	Provides a relevant solution with sufficient clarity and completeness in writing.	2
	Provides more than one relevant solution but with unclear writing.	3
	Produces more than one relevant solution, written clearly and completely.	4
Flexibility	Does not produce a solution or produces one solution in one or more ways, but all are incorrect.	0
	Produces a solution using one method but with inaccuracies in calculation or incorrect results.	1
	Provides a solution with one strategy, a correct calculation process, and accurate results.	2
	Provides more than one solution/strategy, but some answers are incorrect due to calculation inaccuracies.	3
	Produces solutions using more than one strategy with accurate calculations and correct results.	4
	Do not develop a solution or provide an incorrect one.	0
	Develops a strategy inaccurately and without details.	1

Elaboration	Develops a strategy inaccurately and with insufficient details.	2
	Develops a strategy accurately with correct steps but incompletely.	3
	Develops a strategy accurately and completely	4

Data on creative thinking abilities obtained through the pretest and post-test were analyzed using descriptive and inferential statistical methods. To carry out inferential testing, the two independent samples t-test or Mann-Whitney U was used with a significance level of 5% to test the research hypothesis. Before hypothesis testing is carried out, prerequisite tests in the form of normality and homogeneity tests are first applied. The Shapiro-Wilk test was used to test the assumption of normality in the distribution of mathematical creative thinking abilities in the control group and the experimental group. Meanwhile, Levene's test was applied to assess whether the data variance from the two groups was homogeneous. Next, hypothesis testing is carried out via the independent sample t-test or Mann-Whitney U with the help of IBM SPSS Statistics version 25 software. The criterion for hypothesis testing indicates that if the one-tailed p-value exceeds 0.05, there is no statistically significant difference in the creative thinking skills between students engaged in AR-assisted learning and those in conventional learning.

3. Results

The research results showed that there was a difference in increasing students' creative thinking abilities between the experimental class which used AR-based learning and the control class which used conventional learning. In the initial stage, the average pre-test score for the experimental class was 68.75 with a standard deviation of 8.23, while the control class had an average pre-test score of 69.00 with a standard deviation of 8.65. This shows that the initial creative thinking abilities of students in both classes were relatively balanced before being given intervention. After learning, the average post-test score for the experimental class increased to 81.87 with a standard deviation of 8.20, while the control class only achieved an average post-test score of 76.16 with a standard deviation that increased to 10.56. The higher average score increase in the experimental class shows that AR-assisted mathematics learning has a more significant influence on students' creative thinking abilities than conventional learning.

Table 2. Results of Students' Creative Thinking Ability Tests

Group	Mean		Standard Deviasi		N-gain
	Pretest	Post-test	Pretest	Post-test	
Experiment	68,75	81,87	8,23	8,20	0,44
Control	69	76,16	8,65	10,56	0,25

Apart from that, the N-gain value for the experimental class was recorded at 0.44, which is in the medium category, while the N-gain value for the control class was 0.25, which is in the low category. This difference in N-gain values indicates that AR-assisted mathematics learning is more effective in improving students' creative thinking abilities compared to conventional learning methods. The stability of the distribution of grades in the experimental class, which can be seen from the relatively constant standard deviation, shows that AR-assisted mathematics learning produces a more consistent impact on students. In contrast, the increase in standard deviation in the control class indicates a greater variation in results, which may reflect individual differences in the effectiveness of conventional learning. Thus, the results of this research confirm that AR-assisted mathematics learning has a more positive and consistent impact in improving students' creative thinking abilities compared to conventional learning.

In the first question which measures fluency, students in the experimental class had a higher percentage of the highest score (4), namely 53.12% compared to the control class which only

reached 46.67%. Meanwhile, at score 3, the percentage of students in both classes is almost equal, respectively 46.8% for the experimental class and 50.0% for the control class. These results indicate that AR-assisted mathematics learning in the experimental class is more effective in increasing the fluency of creative thinking compared to conventional learning in the control class. In the second question measuring flexibility, the experimental class also showed superior results with the highest score (4), with a student percentage of 50.00%, compared to the control class which only reached 40.0%. However, at a score of 3, the control class had a higher percentage of 60.0%, while the experimental class reached 50.0%. These results indicate that AR-assisted mathematics learning provides a slight advantage in encouraging student flexibility, although the distribution of scores in the control class is more even.

Table 3. Students' Creative Thinking Ability Scores

Item	Score									
	0		1		2		3		4	
	Exp	Ctr	Exp	Ctr	Exp	Ctr	Exp	Ctr	Exp	Ctr
1	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (3.33%)	15 (46.8%)	15 (50.0%)	17 (53.1%)	14 (46.67)
2	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	16 (50%)	18 (60.0%)	16 (50.0%)	12 (40%)
3	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	4 (13.3%)	20 (62.5%)	19 (63.3%)	12 (37.5%)	7 (23.3)
4	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	3 (9.3%)	9 (30.0%)	22 (68.7%)	18 (60.0%)	7 (21.8%)	3 (10%)

Note: First line frequency; second row of percentages

In the third question measuring elaboration, the differences between the two classes became clearer. The experimental class had a greater percentage of score 4, namely 37.5%, compared to the control class which only reached 23.33%. In contrast, with a score of 3, the control class had a higher percentage of 63.33%, while the experimental class reached 62.5%. These results indicate that AR-assisted mathematics learning is more effective in helping students develop ideas in depth, although most students in both classes are still at a score of 3. In the fourth question which measures originality, the experimental class again showed better results with a score of 4, with a student percentage of 21.88%, compared to the control class which only reached 10.0%. At score 3, the experimental class had a higher percentage of 68.75%, while the control class only reached 60.0%. These results indicate that AR-assisted mathematics learning has a more positive impact in increasing students' originality compared to conventional learning.

Overall, these results indicate that AR-assisted mathematics learning is more effective in improving students' creative thinking abilities in the aspects of fluency, flexibility, elaboration, and originality. The experimental class showed a higher score distribution of 4 in almost all aspects compared to the control class, indicating the superiority of AR-assisted mathematics learning intervention in encouraging the development of student's creative thinking abilities. However, there is a small variation in the distribution of 3 scores between the two classes, indicating that the conventional learning approach still provides quite good results for certain students. These results confirm that the use of AR in mathematics learning has a positive and significant impact on students' creative thinking abilities.

Figure 1 shows a comparison of the average score of students' creative thinking abilities on each question between the experimental group which used augmented reality (AR) based learning and the control group which used conventional learning. The results of the analysis showed that the experimental group had a higher average score in all aspects of creative thinking ability than the control group. On the first question measuring the fluency aspect, the experimental group

recorded an average score of 3.53, slightly higher than the control group which obtained 3.40, with a gain of 0.13. These results indicate that augmented reality-based learning provides a small improvement in students' ability to generate ideas fluently. In the second question measuring flexibility, a similar pattern was seen, where the experimental group recorded an average score of 3.50, only slightly higher than the control group which had a score of 3.40, with a gain of 0.10. These results indicate that the effect of AR on students' flexibility is still relatively small compared to other aspects. On the third question measuring elaboration, the experimental group recorded an average score of 3.37, while the control group obtained 3.10, with a gain of 0.27. This increase is greater than the previous problem, indicating that augmented reality-based learning is more effective in helping students develop details and expand their ideas. On the fourth question measuring originality, the biggest difference was seen, with the experimental group recording an average score of 3.12, while the control group recorded 2.80, resulting in a gain of 0.32. These results show that AR-based learning helps students produce more original ideas compared to conventional methods.

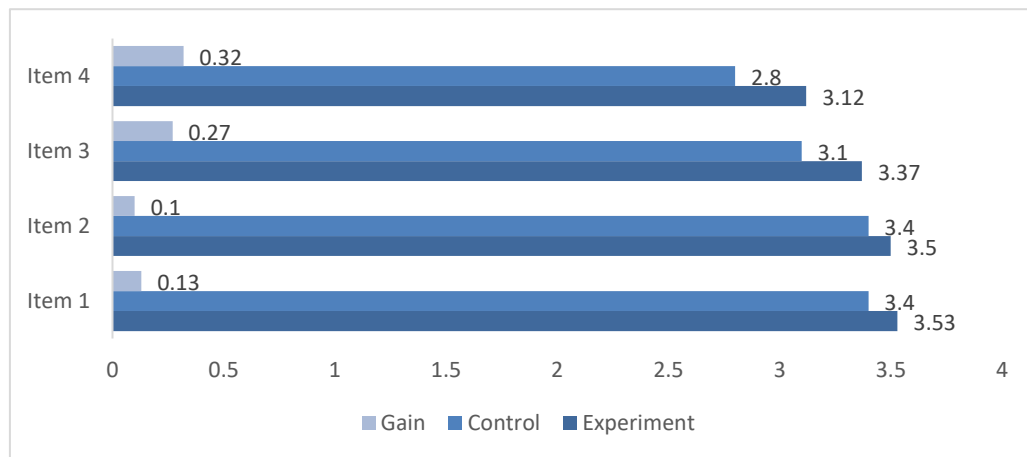


Figure 1: Average Creative Thinking Ability Score Based on Items

Overall, augmented reality-based learning shows better results in all aspects of students' creative thinking abilities, with the most prominent improvements in elaboration and originality. Furthermore, flexibility is an aspect that needs more attention because the gain is relatively low. On the second question measuring flexibility, the experimental group recorded an average score of 3.50, only slightly higher than the control group which obtained 3.40, with a gain of 0.10. This shows that although augmented reality-based learning provides improvements, its influence on student's ability to think flexibly (generating various ideas or solutions) is still small compared to other aspects such as elaboration or originality. Flexibility is an important element in creative thinking because it involves students' ability to move between different perspectives and find alternative solutions.

Table 4. Homogeneity and Normality Test

Group	Pretest		Post-test		N-gain	
	<i>p-value</i> (Levene)	<i>p-value</i> (Shapiro-Wilk)	<i>p-value</i> (Levene)	<i>p-value</i> (Shapiro-Wilk)	<i>p-value</i> (Levene)	<i>p-value</i> (Shapiro-Wilk)
Experiment	0,994	0,019		0,131		0,032
Control		0,141	0,056	0,073	0,542	0,115

Table 4 presents the results of homogeneity and normality tests of pretest, post-test, and N-gain data in the experimental and control classes. In the homogeneity test, data is considered homogeneous if it has a p-value of more than 0.05. The pretest data on creative thinking abilities has a p-value of 0.995, which is greater than 0.05, so it can be concluded that the pretest data in the experimental and control classes have homogeneous variance. Likewise, the post-test data shows a p-value of 0.056, which is also greater than 0.05, so the variance of the post-test data in the two classes is also homogeneous. Apart from that, the N-gain data has a p-value of 0.542, which shows that the variance of the N-gain data in the experimental and control classes is also homogeneous. On the other hand, the Shapiro-Wilk normality test shows that the pretest data in the experimental class and the N-gain data in the experimental class have a p-value of 0.019 and 0.032 respectively, which is smaller than 0.05. This shows that the two groups of data are not normally distributed. On the other hand, the other four groups of data, namely pretest data in the control class, post-test data in the experimental and control classes, and N-gain data in the control class have a p-value greater than 0.05, so that the four groups of data are normally distributed.

Table 5. Pretest Mean Difference Test

Mann-Whitney U	Wilcoxon W	Z	p-value
474.000	939.000	-0.086	0.932

The results of the pretest average difference test between the experimental and control classes using the Mann-Whitney U test showed a p-value of 0.932, indicating that there was no significant difference between the average pretest scores of the two classes. This indicates that before the intervention was carried out, the two groups had relatively the same initial level of ability. Thus, the pretest results show that there is no significant initial bias between the experimental group that will be given augmented reality (AR) based learning and the control group that uses conventional learning methods. This condition ensures that differences in results on the post-test can later be attributed to the intervention provided, namely the use of AR technology, and not due to initial differences between the two groups.

Table 6. Post-test Mean Difference Test

t-test equality of means	t	df	p-value	Mean differences
	2,38	60	0,01	5,70

Table 7. N-gain Average Difference Test

Mann-Whitney U	Wilcoxon W	Z	p-value
225.500	690.500	-3.606	0.00

Post-test mean differences were analyzed using the independent sample t-test because it met the requirements for homogeneity and normality of the data. The results of the post-test average difference test between the experimental and control classes using the t-test for equality of means showed that the t-value was 2.38 with a degree of freedom (df) of 60 and a p-value of 0.01. The mean difference value of 5.70 indicates that there is a difference in the average post-test score of 5.70 points between the two groups. Because the p-value (0.01) is smaller than 0.05, this result shows that the difference in the average post-test score in the experimental class is significantly better than in the control class. This indicates that augmented reality (AR)-based learning has a greater influence on improving students' abilities compared to conventional learning methods. The difference in the average score of 5.70 points reflects that students who learn with the help of AR technology have higher learning outcomes than students who learn using conventional methods, strengthening the effectiveness of technology-based approaches in learning.

Meanwhile, the results of the test for the difference in average N-Gain between the experimental and control groups using the Mann-Whitney U test showed that the p-value of 0.00 was smaller than 0.05. This shows that the increase in students' creative thinking abilities in the experimental class is better than the increase in creative thinking abilities in the control class. These results indicate that the relative increase (N-Gain) in student learning outcomes in the experimental group, which uses augmented reality (AR) based learning, is higher than in the control group which uses conventional learning. Thus, AR technology has proven to be more effective in increasing students' abilities in proportion to the maximum potential improvement that can be achieved. This difference shows that the AR-based approach not only provides superiority in final learning outcomes but also in increasing the level of students' creative mathematical thinking abilities compared to conventional learning methods.

4. Discussion

Creative thinking is one of the important competencies that needs to be mastered in the modern era. Creative thinking is not only an interesting subject but also a phenomenon of practical importance in 21st-century life (Simonton, 2012). Studies related to the integration of AR technology and creative mathematical thinking abilities are still very limited. Therefore, one of the aims of this research is to analyze the effect of AR-assisted mathematics learning on creative mathematical thinking abilities. The experiments described in this research show that students' creative mathematical thinking abilities can be improved through the application of learning assisted by AR technology. This is proven by a significant increase in aspects of post-intervention creative thinking abilities, namely aspects of originality, fluency, flexibility, and elaboration. Through AR-assisted learning, students' creative thinking abilities can be significantly improved.

In general, the findings in this research are in line with research by Anwar (2024) who previously conducted a quantitative survey of AR users and found that the use of AR technology can develop high-level thinking abilities. This is because AR provides students with the opportunity to explore geometric objects in a complex manner (Chen, 2019). A similar thing was also found by Akçayır and Akçayır (2017) who studied the effectiveness of AR in mathematics learning, especially in improving students' spatial skills, which are basic skills leading to creative thinking abilities. This relationship was described in detail by Koparan et al. (2023) that spatial skills have an important role in interpreting, describing, and thinking deeply about objects around them so that it will make it easier for students to solve geometric problems. Furthermore, qualitative research conducted by Faradillah and Maulida (2022) also found that the use of AR technology in mathematics learning can encourage students to solve mathematics problems using various methods and problem-solving strategies. Meanwhile, Koparan et al. (2023) from Zonguldak Bulent Ecevit University in Türkiye found that AR-supported learning methods can significantly improve student learning outcomes in geometry learning.

Furthermore, this research is different from that conducted by Akkuş and Özhan (2017). According to them, the use of AR can indeed improve mathematics achievement but is weak in terms of interactivity. Nevertheless, Flores-Bascuñana et al. (2019) have proven that AR can improve the learning process and is better than learning through classical didactics. Cahyono et al. (2018) also said that the development of AR-based learning can bridge the gap between mathematical concepts and the real world so that it will contribute to students' mastery of concepts and mathematical problem solving abilities. However, Bereczki and Kárpáti (2021) stated that although AR can generally improve the quality of learning, teachers and students need support in how to apply the technology appropriately. Furthermore, when compared with Lee and

Lee (2008) research, the research uses AR-based games to improve the learning experience of preschool and elementary school students. In fact, bibliometric research conducted by İslim et al. (2024) on 645 articles in the WoS, ERIC, and Scopus databases, postulates that the use of AR in mathematics learning can have a positive impact on the ability to solve problems using high-level strategies. Therefore, this research adds insight that AR apart from improving mathematical literacy skills (Hakim et al., 2024), problem-solving abilities (A. N. Cahyono et al., 2020), and developing mathematical computational thinking abilities (Angraini et al., 2023).

The findings of this research also deepen the understanding that AR technology-assisted learning can open up opportunities for students to be more involved and create creative solutions to given mathematical problems. This proposition is also supported by the findings of Alkhabra et al. (2023) and Wang et al. (2024) that AR can encourage students to be more actively involved in learning activities, which greatly supports the development of their creativity. More dynamic interactions with mathematical objects projected by AR enable students to visualize and explore concepts in more depth, which can enrich their creative thinking abilities (Ivan & Maat, 2024). Therefore, this research strengthens the argument that AR, if implemented well, can encourage the development of students' creative thinking skills in mathematics. This is in line with the findings of Sanabria and Arámburo-Lizárraga (2017) who explained that AR is a technology that can be used as a new approach in the pedagogical field to promote creative thinking abilities.

Meanwhile, the importance of creative thinking skills in mathematics education is also reflected in 21st-century education efforts which emphasize the development of high-level thinking skills, including creative thinking, in facing global challenges and rapid technological developments. Therefore, mathematics education must not only focus on mastering basic concepts but also on developing creative thinking skills that can be applied in a broader context. Overall, this research shows that learning assisted by AR technology has great potential to improve students' creative thinking abilities in mathematics, especially in spatial geometry. The integration of AR technology provides a more interactive and immersive learning experience, allowing students to develop the creative thinking skills required to solve more complex mathematical problems. Thus, this research makes a significant contribution to the development of technology-based mathematics learning and students' creative thinking skills.

5. Conclusion

This research shows that learning based on augmented reality (AR) technology has great potential to improve students' creative thinking abilities in mathematics, especially in spatial geometry. This improvement can be seen in the aspects of fluency, flexibility, elaboration, and originality, which reflect the positive impact of AR in encouraging active student involvement, visualizing abstract concepts, and creating creative solutions to mathematical problems. Additionally, interactive and immersive learning experiences through AR help bridge the gap between mathematical concepts and the real world, thereby supporting the development of higher-order thinking skills relevant to 21st-century educational needs. This research also adds insight that AR not only supports mathematical literacy, problem-solving, and geometric thinking skills but can also be an innovative alternative to improve overall creative thinking abilities. Thus, this research contributes to the development of technology-based mathematics learning and students' creative skills.

However, this research has several shortcomings that need to be noted. First, the aspect of AR interactivity with students has not been fully explored in depth, so its impact on learning outcomes may not be optimal. In addition, limitations in sample size and representation of the groups tested limit the generalizability of these findings to a broader population. The relatively

short duration of the intervention is also a limitation because the long-term influence of AR use on creative thinking abilities cannot yet be evaluated. The readiness of teachers and students to integrate AR technology into learning is also not discussed in detail, although this factor can influence the effectiveness of learning. Furthermore, this research only focuses on geometry material, so the effectiveness of AR in the context of other mathematical materials is still unknown.

To overcome this limitation, it is recommended that future research be conducted with a longer duration of AR application to evaluate the long-term impact on students' creative thinking abilities. Similar research could also be extended to other mathematical topics, such as algebra or statistics, to provide a more comprehensive picture of AR's effectiveness. Additionally, a deeper exploration of AR interactivity can be carried out to strengthen student engagement in learning. Qualitative studies that explore students' and teachers' experiences of using AR will also provide additional insight into the challenges and opportunities of implementing this technology. Future research could also investigate infrastructure readiness, teacher training, and student adaptation to AR technology to ensure more effective implementation in various educational contexts. By addressing these shortcomings, future research can expand insight into the application of AR in education and provide greater benefits for improving mathematics learning and developing students' creative thinking abilities.

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