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The Future of Science Learning: Meta-Analysis of the Effectiveness of Augmented Reality in Enhancing Critical Thinking

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Abstract: The development of technology has brought significant changes in the world of education, especially in the field of Natural Sciences (IPA). Critical thinking skills are becoming increasingly important in the ever-evolving information age. Along with that, the importance of education that integrates technology in science teaching is very clear. Augmented Reality (AR) is a technology that combines the real world with digital elements to create interactive and immersive learning experiences. This study evaluates the effectiveness of augmented reality in enhancing students' critical thinking through a meta-analysis approach. A total of 8 articles that met the author's criteria published between 2019 and 2024 were analyzed using paired samples test. The results of this research show that Augmented Reality (AR) technology significantly improves students' critical thinking skills in science learning.

Keywords: Augmented reality; Critical thinking; Meta-analysis; Science learning

Introduction

The development of technology has brought significant changes in the world of education, especially in the field of Natural Sciences (IPA). In recent years, the use of information and communication technology (ICT) in learning has increased rapidly. According to a UNESCO report, more than 1.5 billion students worldwide have been affected by school closures due to the COVID-19 pandemic, which has encouraged the adoption of technology as an alternative learning solution (UNESCO, 2020). This shows that technology is not just an additional tool, but has also become a major component in modern education.

Critical thinking skills are becoming increasingly important in the ever-evolving information age. In a survey conducted by the World Economic Forum, critical thinking skills ranked fourth on the list of most needed skills by 2025 (World Economic Forum, 2020). Science learning not only aims to provide factual knowledge, but also to equip students with in-depth analytical skills, problem solving, and data-based decision making.

Along with that, the importance of education that integrates technology in science teaching is very clear. The use of technology can help students not only understand scientific concepts but also encourage them to think critically about the information they receive. In this context, innovative approaches that combine technology and active learning methods are becoming increasingly relevant.

Augmented Reality (AR) is a technology that combines the real world with digital elements to create interactive and immersive learning experiences. Its definition covers a wide range of applications, from games to education, which allow users to interact with virtual objects in their real environment. According to Azuma (1997), Chang et al. (2022), Rais et al. (2024), and

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Pamorti et al. (2024), AR is a system that has three characteristics: integration of reality and virtuality, real-time interaction, and 3D registration.

In the context of education, AR offers a variety of applications that can enhance students' learning experiences. For example, AR applications in science learning can enable students to view cellular structures in three dimensions, understand physics concepts through interactive simulations, and visualize complex biological processes. Research by Salsabila et al. (2024) shows that the use of AR-based learning modules can increase students' motivation and conceptual understanding, as well as encourage active involvement in the learning process.

Through AR technology, students are not only recipients of information, but can also interact with the subject matter directly. This can increase the appeal of science learning, which is often considered difficult and boring by students. With a more interesting learning experience, it is hoped that students will be more motivated to develop their critical thinking skills.

This article aims to evaluate the impact of using Augmented Reality in science learning on students' critical thinking skills. Critical thinking is the ability to analyze information, evaluate arguments, and make decisions based on available evidence. In the context of education, these skills are essential to help students address future scientific and social challenges.

The importance of critical thinking in science learning cannot be ignored. Students who are skilled in critical thinking can develop the ability to solve problems, adapt to change, and innovate in scientific research. Research by Sylvia et al. (2021), Saputra et al. (2022), Fadiah et al. (2024), and Faiza et al. (2022) shows that AR can contribute to improving critical thinking skills by providing real context to the scientific concepts being taught.

Why is AR considered to have the potential to improve these skills? One reason is AR's ability to present information in a more engaging and interactive way. By seeing objects and concepts directly, students can more easily understand and analyze information, thus encouraging them to think critically. In addition, a fun learning experience through AR can increase students' interest in science lessons, which in turn can improve their critical thinking skills (Nusroh, 2021; Rahmawati & Setiaji, 2025; Wartono et al., 2019; Zan & Asrizal, 2024; Rahmayani et al., 2024; Fajari et al., 2023; Azzam et al., 2015; Faridi et al., 2021; Pangestu & Wulandari, 2023).

Method

The type of research used in this study is meta-analysis. Meta-analysis itself is an effort by researchers to summarize various research results quantitatively or as a way to re-analyze existing research results (Soetjipto, 2016). The collection of research data was carried out by searching a number of national journals via Google Scholar, assisted by the keywords "augmented reality", "critical thinking", and "high schools". The results of searching for articles through various journals obtained 8 articles that met the author's criteria, which would later be used as research subjects. The criteria referred to in selecting the selected articles are articles that contain values before being given augmented reality (AR) media integration and value data after being given augmented reality (AR) media integration. Data before and after being given treatment in the form of augmented reality (AR) media integration, then sought whether there was an increase through the difference in the initial and final averages through the paired samples test assisted by SPSS version 25 via Windows 10.

Result and Discussion

The results of the integration research (AR) in science learning in secondary schools in the form of journal articles included in this research include:

Development of Interactive Teaching Modules Assisted by Augmented Reality in Junior High School Science Learning to Improve Critical Thinking Skills by Salsabila et al. (2024).
Development of 3D STEM-Based Modules to Improve Students' Critical Thinking Skills (Sholikhah & Arif, 2024).
Development of Augmented Reality-Based Physics Learning Media to Improve Critical Thinking Skills of Grade XI Students of SMA/MA (Nusroh, 2021).
Development of Augmented Reality-Based Learning Modules on Cell Material to Improve Critical Thinking Skills of Students at SMA Negeri 1 Tibawa (Anapia et al., 2024).
Improving Students' Critical Thinking Skills Through the Problem Based Learning Model Assisted by Augmented Reality by Isatunada et al. (2023).
Development of STEM-Based Teaching Materials by Utilizing Augmented Reality to Improve Critical Thinking Skills by Oktaviyanti et al. (2023).
The Effectiveness of Augmented Reality on Students' Higher Order Thinking Skills in Biology Learning by Sylvia et al. (2021).
Application of Guided Inquiry Learning Model in the Form of Augmented Reality for Students to Increase Interest and Understanding of Science Concepts by Aryani et al. (2019).

Table 1. Results of AR Integration Analysis in Science Learning to Improve Students' Critical Thinking Skills

Tittle	Authors	Improving Learning Outcomes			Gain (%)	Category
		Pre	Post	Gain		
Development of Interactive Learning Modules Assisted by Augmented Reality in Junior High School Science Learning to Improve Critical Thinking Skills	Salsabila et al. (2024)	41.41	81.25	39.84	68	Medium
Development of 3D STEM-Based Modules to Improve Students' Critical Thinking Skills	Sholikhah & Arif (2024)	64	83.5	19.5	56	Medium
Development of Augmented Reality-Based Physics Learning Media to Improve Critical Thinking Skills of Grade XI SMA/MA Students	Nusroh (2021)	66.67	80.5	13.83	41.50	Medium
Development of Augmented Reality-Based Learning Modules on Cell Material to Improve Critical Thinking Skills of Students of SMA Negeri 1 Tibawa	Anapia et al. (2024)	50.76	74.99	24.23	48.90	Medium
Improving Students' Critical Thinking Skills Through Problem Based Learning Model Assisted by Augmented Reality. National Science Seminar XIII	Isatunada et al. (2023)	76.47	82.35	5.88	53	Medium
Development of STEM-Based Teaching Materials by Utilizing Augmented Reality to Improve Critical Thinking Skills	Oktaviyanti et al. (2023)	56.75	86.5	29.75	68.57	High
The Effectiveness of Augmented Reality on Students' Higher Order Thinking Skills in Learning	Sylvia et al. (2021)	31.8	69.8	38	58	Medium
Implementation of Guided Inquiry Learning Model in the Form of Augmented Reality for Students to Increase Interest and Understanding of Science Concepts	Aryani et al. (2019)	33.35	93.38	60.03	89	High
Average influence of AR integration in science learning		52.65	81.53	28.88	60	High

Table 2. Paired Sample Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	Pretest	52.6513	8	16.24239	5.74255
	Posttest	81.5338	8	7.08298	2.50421

Table 3. Paired Sample Correlations

	N	Correlation	Sig.
Pair 1 Pretest & Posttest	8	.098	.817

Table 2 states that in the study the average value of the pretest was 52.6513, indicating students' critical thinking skills before using AR-based learning media. After using AR, the average posttest value increased to 81.5338, indicating a significant increase in students' critical thinking skills. With the number of schools that were the research sample being 8 schools. The standard deviation value in the pretest was 16.24239, indicating a fairly large variation in students' initial critical thinking skills. In the posttest, the standard deviation decreased to 7.08298, which means that the results after AR learning were more homogeneous. The pretest had a standard error of 5.74255, while the posttest had a smaller standard error of 2.50421, indicating more accurate results after the learning intervention using AR.

These results indicate a significant increase in the average critical thinking skills of students after learning using Augmented Reality-based media. The decrease in the standard deviation value also indicates that learning outcomes are more consistent among students after the intervention. These data provide strong evidence that the use of AR technology in science learning is effective in improving students' critical thinking skills.

Table 3 shows that the correlation value between pretest and posttest is 0.098, indicating a very weak relationship between pretest and posttest scores. This shows that students' initial scores (pretest) are not directly correlated with their final results (posttest) after using Augmented Reality (AR)-based learning media. The significance value is 0.817, which is much greater than the standard significance level of 0.05. This shows that the relationship between pretest and posttest is not statistically significant. These results indicate that the use of Augmented Reality as a learning medium has the potential to change the pattern of student learning outcomes without being influenced by their initial scores. In other words, students with low pretest scores can still get significant improvements in the posttest after AR-based learning interventions. These results support the argument that Augmented Reality can be an inclusive, effective learning tool for all students, regardless of their initial abilities.

Table 4 states the results of the Paired Samples Test analysis show a significant difference between the pretest and posttest scores of students after using Augmented Reality (AR)-based learning media. The average value of the difference between the pretest and posttest is -28.88250. This indicates an increase in the average score of 28.88 points from the pretest to the posttest. The standard deviation of 17.06912 indicates a variation in scores between students, but remains within acceptable limits for a small sample size. The standard error value of 6.03485 indicates an estimate of the level of error in measuring the average difference. The confidence interval for the difference in scores is in the range of -43.15264 to -14.61236. This range does not include zero, thus strengthening the conclusion that there is a significant difference between the pretest and posttest. The t value of -4.786 with degrees of freedom (df) 7 indicates a high level of significance of the difference in scores. The significance value of 0.002 is smaller than 0.05, so the difference in pretest and posttest scores is statistically significant. The results of the Paired Samples Test show that Augmented Reality-based learning significantly improves students' learning outcomes in the critical thinking aspect. The increase in the average score of 28.88 points shows the effectiveness of AR learning media in creating a deep and meaningful learning experience. These results support the use of Augmented Reality technology as a learning innovation in the future, especially in science learning, to help students develop better critical thinking skills.

Table 4. Paired Sample Test

	Mean	Std. Deviation	Std. Error Mean	95% Confidence interval of the difference		t	df	Sig. (2-tailed)
				Lower	Upper			
Pair 1 Pretest-Posttest	-28.88250	17.06912	6.03485	-43.15264	-14.61236	-4.786	7	.002

Augmented Reality (AR) has become one of the promising technologies in education, especially in Natural Science (IPA) learning. The latest meta-analysis shows that the use of AR in education can significantly improve students' critical thinking skills. In a study conducted by Anapia et al. (2024), it was found that students who used AR-based learning modules showed an increase in critical thinking skills of up to 30% compared to traditional learning methods. These data show that AR not only increases students' interest but also helps them understand complex concepts in IPA.

The main results of the data analysis indicate that AR can improve student engagement with learning materials. In a study conducted by Aryani et al. (2019), students who learned using AR showed a higher level of participation in class, which contributed to increased conceptual understanding. In addition, data visualization from the study showed that students who used AR had higher test scores compared to those who used conventional methods. This suggests that AR can be an effective tool in improving student learning outcomes.

Data visualization that supports this finding can be seen from the graph showing a comparison of exam scores between two groups of students, one group using AR and one group using traditional methods. The graph shows a significant difference, where the AR group has a higher average score. This finding is in line with the results of other studies showing that AR can increase student learning motivation and engagement in the learning process (Sylvia et al., 2021).

Furthermore, the analysis shows that the effectiveness of AR in improving critical thinking is also influenced by the context of use. For example, the use of AR in science laboratory learning provides a more immersive learning experience, where students can see real-time experimental simulations. This helps students understand the scientific process better and improves their ability to think critically about the results of the experiments carried out (Nusroh, 2021).

Thus, it can be concluded that AR has great potential to improve the effectiveness of science learning. Based on the existing meta-analysis, AR not only improves learning outcomes but also equips students with the critical thinking skills needed to face future challenges. The application of AR in science learning has shown a significant impact in various educational contexts. One interesting case study is the application of AR in Senior High School (SMA) Negeri 1 Tibawa, where AR-based learning modules were applied to cell material. The results showed that students involved in learning with AR experienced a 40% increase in understanding of cell concepts compared to students who only used textbooks (Anapia et al., 2024).

In addition, in the context of elementary schools, the use of AR to teach the concept of the five senses also shows positive results. In a study conducted by Marfilinda et al. (2022), Indrajatun et al., (2022), Jameh et al. (2023), Adilah et al. (2025), Hasan et al. (2021), Istiyani et al. (2018), and Mukhlisa (2021) students who learned with AR showed a better understanding of the concepts taught, and were able to identify existing misconceptions. This shows that AR can be used to bridge the gap in understanding that often occurs among students.

The comparison of the results between the use of AR and traditional methods shows that AR not only improves understanding, but also students' interest in learning. In a study by Oktaviyanti et al. (2023), students who used AR-based teaching materials reported that they were more interested and motivated to learn science compared to students who used conventional methods. These data show that AR is able to create a more interactive and enjoyable learning environment.

However, it is important to note that the effectiveness of AR is also influenced by factors such as teacher training and the readiness of technological infrastructure in schools. In some schools that lack technological facilities, the implementation of AR may not be as effective as in schools that are ready. Therefore, support from the government and educational institutions in providing adequate facilities is needed to maximize the potential of AR in education (Isatunada et al., 2023; Sulthon et al., 2025; Aji et al., 2025; Anggraini et al., 2024; Muliana & Nufus, 2024; Lespita et al., 2023).

By looking at these case studies and comparing the results, it is clear that AR has a positive impact on science learning. With the right application, AR can be an effective tool in improving students' understanding and critical thinking skills at various levels of education.

The potential for developing AR as a future technology for education is enormous. With the advancement of technology that continues to develop, AR can be integrated into the education curriculum in a more innovative way. For example, the development of an AR application that allows students to conduct virtual science experiment simulations can be a solution to overcome the limitations of laboratories in schools. This will allow students to learn practically without having to be tied to physical facilities that may not always be available (Salsabila et al., 2024).

The implications for curriculum and teaching methods are broad. Curriculums that integrate AR can be designed to encourage students to collaborate on AR-based projects, where they can work in groups to solve scientific problems. This will not only improve critical thinking skills, but also social and collaboration skills among students. In this context, AR can be a tool that supports project-based learning, which is increasingly popular in modern education (Sholikhah & Arif, 2024).

In addition, AR can also be used to enrich learning experiences outside the classroom. For example, AR applications can be used to conduct virtual tours of scientific locations, such as museums or national parks, allowing students to learn in a broader context. This will provide students with a more immersive and contextual learning experience, as well as encourage their curiosity about the world around them (Oktaviyanti et al., 2023; Fajari & Meilisa, 2022; Hsu et al., 2018; Faridi et al., 2020; Dilmen & Atalay, 2021; Faridi et al., 2020; Shoutthaboualy et al., 2021; Sirakaya & Alsancak-Sirakaya, 2018; Syawaludin et al., 2019; Waliyuddin & Sulisworo, 2021; Damanik & Fajari, 2025).

However, challenges remain in the widespread application of AR in education. The availability of adequate hardware and software, as well as adequate training for teachers, are key factors in the success of AR implementation. Therefore, collaboration between the government, educational institutions, and the technology industry is essential to create an ecosystem that supports the use of AR in education (Nusroh, 2021). Overall, the prospects for AR as a future technology in education are very promising. With the right approach, AR can be a revolutionary tool in improving the quality of science learning and equipping students with the critical thinking skills needed to face future challenges.

Conclusion

Effectiveness of AR in improving critical thinking: Research shows that Augmented Reality (AR) technology significantly improves students' critical thinking skills in science learning. This is achieved through interactive and immersive learning experiences that allow students to understand complex concepts more easily and deeply. The average increase in critical thinking skills reached 28.88 points after using AR, as reflected in various meta-analyses.

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B.D.K.: conceptualized the research, research procedures, analyzed the data and wrote the article; M.S.H. and S.: supervised the writing of the article, reviewed and validated the research instruments used.

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There is no conflict of interest.

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