MODESTUM EURASIA Journal of Mathematics, Science and Technology Education, 2025, 21(1), em2559
ISSN:1305-8223 (online)
OPEN ACCESS Research Paper https://doi.org/10.29333/ejmste/15796

Enhancing student's interactivity and responses in learning geometry by using augmented reality

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Received 13 July 2024 ▪ Accepted 10 December 2024

Abstract
This study investigates the impact of augmented reality (AR) applications on geometry learning among 56 eighth-grade students in Indonesia. Over four weeks, students were taught about basic three-dimensional figures such as cubes, rectangular cuboids, pyramids, and prisms using AR materials. We measured student interactivity and responses through observation and a questionnaire. The results showed a significant increase in student interactivity and overwhelmingly positive responses to the subject matter. A questionnaire revealed that students found AR materials satisfactory, easy to use, and helpful in concretizing abstract concepts. Most students expressed a desire to use AR applications in other subjects as well.

Keywords: augmented reality, interactivity, learning geometry, student's responses

INTRODUCTION

Some branches of junior high school mathematics, such as geometry, require learning media that can develop students' visualization abilities, particularly when learning about solid figures. Despite this need, many teachers still rely heavily on textbooks as their primary teaching tool (Amir & Sari, 2018). Textbooks typically present geometric figures as static images, which can be challenging for students to interpret and visualize in three dimensions (Glasnovic Gracin, 2018). This limitation hinders students' ability to fully grasp geometric concepts. Visualization plays a crucial role in understanding and solving problems related to geometry, as it helps students mentally manipulate and explore figures, leading to a deeper comprehension of the material (Puloo et al., 2018).

While the secondary school curriculum includes three-dimensional space geometry to enhance spatial skills, the primary focus remains on two-dimensional plane geometry (Cao, 2018). Research shows that this imbalance in emphasis can create difficulties when students encounter complex three-dimensional figures, as they may lack sufficient practice in spatial reasoning (Maqoqa, 2024). For example, after learning about Euclidean geometry in the plane, students might struggle to visualize how a two-dimensional circle (with an area formula of πr^2) extends into a three-dimensional sphere (with a volume formula of $\frac{4}{3}\pi r^3$). This difficulty arises because textbooks typically present geometric figures as static images, making it challenging for students to interpret and visualize them in three dimensions (Bülthof et al., 1995). Without dynamic tools for visualizing how a circle expands into a sphere, students may rely solely on memorizing formulas without fully grasping the spatial relationships between objects, leading to a superficial understanding of these concepts.

Despite the importance of developing spatial skills, most mathematics teachers continue to use traditional textbooks to teach geometric concepts and conduct expository teaching activities (Ratnasari et al., 2018; Rezat et al., 2021; Yunianta et al., 2023). These methods often fail to address the logical and spatial concepts inherent in geometry, such as spatial perception, spatial visualization, mental rotation, spatial relationships, and

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Contribution to the literature

- This research contributes to the growing body of literature on the benefits of AR in education, particularly in geometry learning, by demonstrating the effectiveness of AR-based learning media in enhancing students' understanding and engagement.
- Addressing the common challenge of visualizing three-dimensional figures, the study reveals a significant increase in student interactivity and motivation. The unique approach of combining interactive AR technology with traditional learning methods underscores AR's ability to personalize and improve the learning experience.
- The findings suggest that AR can help students better grasp complex geometric concepts by making them easier to visualize and understand. This aligns with the conclusion that AR has the potential to transform traditional teaching methods, significantly enhancing student engagement and comprehension of abstract ideas, and offering valuable insights for future educational strategies and the integration of technology in the classroom.

spatial orientation (Potkonjak et al., 2016; Su & Wu, 2021; Trivedi, 2024). Consequently, students may struggle to develop a deep understanding of geometric figures and their properties. This limitation restricts their ability to apply these concepts in real-world scenarios, where visualizing and manipulating three-dimensional objects is often necessary. A study by Hwang et al. (2020) found that students who participated in learning activities supported by the ubiquitous geometry system showed significant improvements in geometric reasoning and spatial estimation abilities in real-world scenarios, compared to those who did not.

Researchers have examined and revealed the contributions of various teaching materials to technology-supported education (Müller & Wulf, 2020). In recent years, augmented reality (AR) applications have been increasingly integrated into diverse teaching and learning environments through technology-enhanced materials. AR has the potential to significantly boost student interaction by offering immersive and interactive learning experiences (Baxter & Hainey, 2024; Cheng & Tsai, 2019). Capone and Lepore (2020) found that AR media enhances student involvement by allowing direct interaction with the learning material, while Videnovik et al. (2020) observed that AR increases students' motivation and enthusiasm, making learning more enjoyable and engaging. Additionally, AR media can improve critical thinking and problem-solving skills by promoting interactive, hands-on experiences (Karagozlu, 2018; Syawaludin & Rintayati, 2019). Dunleavy et al. (2009) also highlighted how simulations and interactive games within AR can drive students to actively participate and interact in their learning. Moreover, using AR in collaboration and project-based learning environments can foster social skills, enhance group interaction, and increase overall student interactivity (Wang, 2020).

In addition to enhancing interaction, AR media provides students with challenging tasks that encourage active participation, critical thinking, and deeper engagement with learning materials (Chiang et al., 2014). The ability to create and manipulate three-dimensional spaces and figures helps students better understand geometric concepts. This comprehension enables students to identify and analyze real-world objects, offering a new perspective on three-dimensional figures (Clements & Battista, 1992). By gaining a deeper understanding of spatial properties, students are better equipped to analyze, communicate, and relate these concepts to everyday life.

Essentially, elementary schools have been teaching students about three-dimensional figures or objects since their enrollment. This foundational concept is often included in various elementary school curricula, such as The Common Core State Standards Initiative (2022), which outline specific expectations for geometry in early education. For instance, grade 1 introduces students to three-dimensional shapes such as cubes, rectangular cuboids, cones, cylinders, and spheres. They learn to identify and describe these shapes based on their attributes. By grade 2, the curriculum expands to include more complex activities, such as composing and decomposing three-dimensional shapes, which reinforces their understanding of spatial relationships. As students progress, they apply their knowledge of these shapes in real-world contexts, which enhances their problem-solving skills and fosters a deeper appreciation for geometry in everyday life. These foundational competences is crucial for understanding more advanced lessons on three-dimensional figures and objects (Stieff et al., 2005). Elementary school materials on three-dimensional figures and objects aim to familiarize students with basic figures and objects, tailoring them to their cognitive abilities. From elementary school to university, the Indonesian curriculum incorporates three-dimensional figure or object material to foster the necessary proficiency in these areas (Prabowo et al., 2017). Every student shall try to develop their spatial ability and sense, which are very useful in solving problems in mathematics and everyday life (Sorby & Panther, 2020). Vorstenbosch et al. (2013) emphasizes the importance of spatial ability in engineering sciences and mathematics, particularly in geometry. This aligns with the perspective of Wai et al. (2009), who assert that spatial ability plays a crucial role in the development of science, technology, engineering, and mathematics skills.

However, in Indonesia, most mathematics teachers still rely on traditional textbooks to teach geometric concepts and conduct expository teaching activities (Ratnasari et al., 2018; Rezat et al., 2021; Yunianta et al., 2023). These methods often focus on important logical concepts of space, such as spatial perception, spatial visualization, mental rotation, spatial relationships, and spatial orientation (Potkonjak et al., 2016; Su & Wu, 2021; Trivedi, 2024). Despite the limitations of traditional methods, some researchers in Indonesia have begun developing AR applications for education (Rohendi et al., 2018). For instance, Nindiasari et al. (2024) developed AR Mathematics media with a STEAM approach, which has been shown to improve problem-solving abilities in geometric concepts. Similarly, Pujiastuti and Haryadi (2024) demonstrated that AR learning media effectively enhances geometric thinking abilities. Despite its potential, the use of AR for geometry education in Indonesia remains limited. According to Permatasari and Andayani (2021), teachers still face challenges in monitoring whether students correctly understand the material during the geometry learning process when using AR. Despite the high acceptance of AR for geometry learning, the evaluation of this acceptance has primarily relied on the personal perceptions and opinions of students and teachers (Malizar & Johar, 2021). There has been a lack of observational studies measuring how students interact with AR during geometry lessons. Such observational studies are crucial for capturing the full extent of student interactions and their acceptance of AR in geometry education.

In this study, we applied a medium called AR geometry applications to investigate student interactivity and their responses when using AR geometry. The AR application displays three-dimensional objects in detail, allowing students to view and interact with every part of the object. The purpose of this study is to streamline the process of learning three-dimensional figures or objects, pique students' interest, and offer them fresh opportunities for interaction through learning media. The research problem is formulated, as follows:

(1) What is the level of students' interactivity when they use AR geometry as a learning medium?

(2) What are the responses of students when they use AR geometry as a learning medium?

To address these questions, we measured student interactivity and responses through observation and a questionnaire conducted over a four-week period. During this time, students engaged with AR materials designed to enhance their understanding of geometric concepts such as cubes, rectangular cuboids, pyramids, and prisms. With the revealed level of student interactivity and responses, this research can serve as a foundational reference for the selection of AR in geometry learning.

LITERATURE REVIEW

Interactivity

Interactive geometry learning is essential as it enables students to actively engage in the learning process, leading to enhanced conceptual knowledge and critical thinking abilities (Di Paola et al., 2013; Jelatu & Ardana, 2018; Rezat et al., 2021). Interactive learning media, such as dynamic geometry software and immersive media, can enhance comprehension of abstract topics by making them more tangible and accessible (Price et al., 2020). Engaging in direct interaction with learning materials empowers students to independently explore, conduct experiments, and make discoveries, enabling them to develop a more profound comprehension (Chang et al., 2016). Moreover, interactive learning fosters collaboration and discourse among students, thereby enhancing their learning motivation and social aptitude. Research indicates that students who acquire knowledge through interactive instructional approaches have superior retention rates and demonstrate enhanced proficiency in applying geometric principles to practical scenarios (Pashler et al., 2008).

Tomiczková and Lávička (2013) discovered that computers could provide a rich framework for interaction between learners and geometric figures. Chang et al. (2016) proposed that multimedia learning materials lead to noticeable improvements in students' ability to visualize, analyze, describe, rationalize, and organize geometric information. Alkhateeb and Al-Duwairi (2019) found that combining mobile devices with manipulation tools creates an interactive learning environment that supports the development of students' geometric understanding. Building on these findings, exploring the use of AR could further enhance interactive learning by offering new dimensions of engagement and visualization.

Geometry Learning

Due to the teaching of three-dimensional geometric objects in two-dimensional plane geometry lessons, students often struggle academically and harbor negative attitudes towards geometry classes (Ibili & Sahin, 2015; Pavlovicova & Zahorska, 2015; Tsao, 2017). Geometry closely relates to students' spatial skills. While the curriculum includes three-dimensional space geometry to enhance spatial skills, the primary focus is on two-dimensional plane geometry (Cao, 2018). When comparing a sphere and a cube with the same radius and edge length, respectively, it is challenging to intuitively determine which shape is larger based solely on their dimensions. Therefore, to compare two objects correctly and easily, there is a need for manipulations that are three-dimensional (Bülthoff et al., 1995). These manipulations allow students to interact with and visualize the shapes from various angles and perspectives. By rotating and adjusting the objects in a three-dimensional space, students can better understand their volume and surface area relationships, making it easier to determine which shape is larger or how they differ in size. If students rely solely on mathematical formulas and regulating geometry to compare the volumes of two bodies, they lack the necessary understanding of these formulas and objects.

Bishop (1980) identified two abilities that underlie the conceptualization of geometric objects. The first ability was to interpret image information. The process of visualization involved manipulating the visual image and relating it to a corresponding mental image. The second ability managed the visualization process and presented geometrical concepts using figures, figures, and descriptive narratives. According to Clements and Battista (1992), learners with enhanced visualization skills can observe objects from various perspectives and judge and manipulate their mental images.

However, in the past, most mathematics teachers used traditional mathematics textbooks to teach concepts of geometric figures and conduct expository teaching activities, in which the concept of geometric figures contains important logical concepts of space such as spatial perception, spatial visualization, mental rotation, spatial relationships, spatial orientation, etc. (Potkonjak et al., 2016; Su & Wu, 2021; Trivedi, 2024; Yunianta et al., 2023). While effective, these traditional approaches often lack interactive elements that can engage students more deeply (Glasnovic Gracin, 2018). Recent research suggests that incorporating interactive materials, such as AR, can significantly enhance student engagement and learning (Rossano et al., 2020). AR provides dynamic and immersive experiences that allow students to interact with geometric figures in three dimensions, thereby fostering a more engaging and effective learning environment.

Augmented Reality and Geometry

Geometry learning benefits from engaging and interactive media. Virtual reality has been shown to enhance interaction and learning outcomes; however, its implementation is often limited by high costs and sophisticated infrastructure requirements (Hilfert & König, 2016; Trivedi, 2024). In contrast, AR offers a more practical and affordable alternative while still providing representative and interactive visualization (Schutera et al., 2021). AR allows students to interact with three-dimensional geometric objects using common devices such as smartphones or tablets, enabling abstract concepts like geometric figures and transformations to be visualized realistically (Cheng & Tsai, 2013; Daniela, 2020; Ibáñez et al., 2018). Despite the potential of AR, its application in Indonesia remains limited due to a lack of resources and an open platform for development. The production of digital learning media such as AR cannot depend solely on teachers considering the limited development capabilities in terms of knowledge and technical devices (Ramadhan et al., 2024). Therefore, collaboration among the government, educational institutions, and technology developers is essential to provide and popularize AR learning media. Training for teachers and the development of user-friendly AR applications could significantly enhance geometry learning in Indonesia, making it more engaging, interactive, and practical for students.

While AR offers promising interactive possibilities, it does not always guarantee positive learning outcomes (Khan et al., 2019). For instance, AR's effectiveness can be compromised if the virtual elements are not well-integrated with the real-world context or if students do not engage effectively with the AR content. To visualize AR 3D objects, users typically view them through the camera of mobile devices, which are widely supported on Android and iOS platforms (Arena et al., 2022). AR applications overlay virtual objects onto the captured real-world view by the device's camera, enabling users to simultaneously view the real world and the virtual elements (Azuma, 2020).

METHODOLOGY

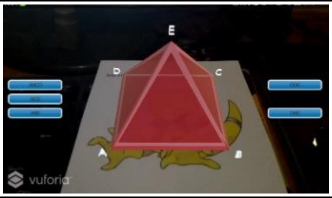
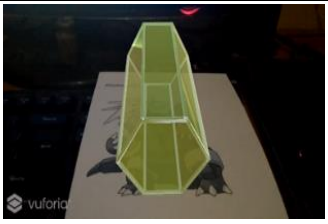
Research Design

This study, a mixed-methods research project, combines qualitative and quantitative methods to examine the impact of teaching geometry subjects of three-dimensional objects with AR-supported materials on students' interactions and responses. To measure student interactivity, this research conducts an observation during four weeks of meetings using AR geometry. Subjects taught during the 4 weeks of meetings include: 1st week meeting material about cubes; 2nd week about rectangular cuboids; 3rd week material about pyramids; 4th week about prisms. After the lessons were completed, we asked participants to respond to the questions in an online survey questionnaire developed by the researcher. We use Likert-scale to assess the students' views in a quantitative manner.

Sample

The study's population was defined by the accessible population type (Büyüköztürk, 2012). The study's participants were students studying at a junior high school in the west Java region of Indonesia in the academic year 2022-2023. 56 students in the 8th grade voluntarily participated in the study. This research

Table 1. Teaching plan

Week	Content	Examples of a problem to be solved	AR visualization (Authors' own documentation and product)
1st	• Basic elements of cubes (number of edges, edge length, number of diagonals, & diagonal length) • Expansions of cubes (number of surfaces & surface figures) • Surface area and volume calculations in cubes are explained.	Calculating the total surface area, volume of the cube, and the length of the cube's diagonal.	
2nd	• The basic elements of the pyramid (number of segments, length of segments, & height) • Expansion of pyramids (number of surfaces, surface figures, & vertex) • Surface area and volume calculations in pyramids were explained.	Calculating the surface area and the volume of the pyramid.	
3rd	• Basic elements of the rectangular cuboids (number of segments, length of segments, width, & height) • Expansion of the rectangular cuboids (number of diagonals, surfaces, & surface figures) • Surface area and volume calculations in rectangular cuboids are explained.	Calculating the surface area, volume, and length of the body diagonal.	
4th	• Obtaining prisms of different heights with the same volume • Exercises related to obtaining prisms with the same volume, but different lengths of segments were done.	Calculate two prisms that have the same volume of 120 cubic centimeters. One prism has a base area of 20 cm^2, and the other has a base area of 15 cm^2. Calculate the heights of both prisms.	

employs a one-shot case study. We treated the sample as a single group and observed them after they had received the treatment.

Data Collection

This study attempts to measure the interactivity of AR based on observations of interactions by observers, in this case researchers, along with a questionnaire to gather student responses. Observations focus on revealing total interaction, time of interaction, quality of interaction, response to the application, user interaction, personalized interactions, impact of interaction, responsiveness, customization, and collaboration aspect. To ensure the quality and accuracy of the assessment tools, the instrument for measuring interactivity was reviewed by an expert and adhered to established patterns from previous tools.

To further probe and explore based on the participants' responses, we asked a group of students who participated in AR geometry lessons to share their thoughts and experiences through a questionnaire. The questionnaire consisted of 8 semi-structured questions designed to gather feedback on the AR geometry teaching materials and the learning experience during the lessons. The eight semi-structured questions consist of three parts. The first part focuses on usability, reliability, and compatibility of the application. The second part focuses on interactivities, motivation, and suitability of field of studies. The third part focuses on the visual and layout of the application. The study utilized a Likert scale to assess students' interactivity with AR geometry in learning geometry, along with a questionnaire to gather their responses. The questionnaire was rigorously tested for validity and reliability, achieving Cronbach's alpha value of 0.76, indicating strong internal consistency. Cronbach's alpha value confirms that the instrument used is reliable and valid for evaluating students' interactions and perceptions of the AR geometry application.

Research Procedure

In this study, AR applications were integrated into teaching the geometry of three-dimensional objects to 8th grade students. We conducted the AR-enhanced lessons for a total of eight hours over a period of four weeks. Following the completion of the three-dimensional object topic, we administered an interactive learning and responses scale to all students to evaluate their experience with geometry learning.

We introduced the AR applications to the students before incorporating them into the teaching process. We explained the application's content, how to use it, and how it related to the course. We use AR geometry that has been developed previously (**Table 1**). Firstly, we

Table 2. Categorization of data analysis for students' interactivity and response

Percentage (P) (%)	Interpretation
P ≤ 25	Very poor
25 < P ≤ 50	Poor
50 < P ≤ 75	Good
75 < P ≤ 100	Very good

installed the AR geometry application on the students' mobile devices to demonstrate the general properties of three-dimensional objects and their views from various angles during the lessons. During the application process, a predefined educational plan effectively incorporated AR materials, delivering three-dimensional objects and their properties.

AR materials enabled interactive teaching. Problem situations were presented to the students for them to transfer their gains to real life situations. While the control group students solved the problems by using the formulas required for length measurement, diagonal, area measurement, and volume measurement, the students were expected to create a solution for the problems by creating appropriate figures through the application. During the problem-solving process, the teacher provided guidance to the students on how to solve the problem. The students endeavored to devise a solution that would lead to the desired outcome.

Data Analysis

Upon completing the topic on three-dimensional objects, students were surveyed on their experiences in interactive learning and responses with AR geometry learning. The survey employed a Likert scale, and the results were calculated using Eq. (1).

$$P = \frac{Total\ score}{ideal\ score} \times 100\%, \quad (1)$$

where P is percentage score and ideal score = maximum score each item × total of respondents × total items.

These results were then categorized based on percentage scores, as outlined in **Table 2**. To convert and categorize the scale, we used the top-box method to divide 100% into four categories equally.

Furthermore, to measure the significance of differences in student interaction scores between weeks of meetings, a one-way ANOVA analysis assessment was carried out. As a prerequisite, Shapiro-Wilk normality and homogeneity tests were carried out.

RESULTS

Implementation of AR-Based Geometry Learning Media

This study uses AR as the learning medium for the three-dimensional object lesson. We deliberately use an image in the form of a figure to display three-dimensional objects. The lesson covers cubes, prisms, beams, and pyramids as examples of three-dimensional objects. This lesson focuses on determining the face diagonal, the space diagonal, the height or altitude, and the slant height of three-dimensional objects. **Figure 1** displays the AR Media illustration.

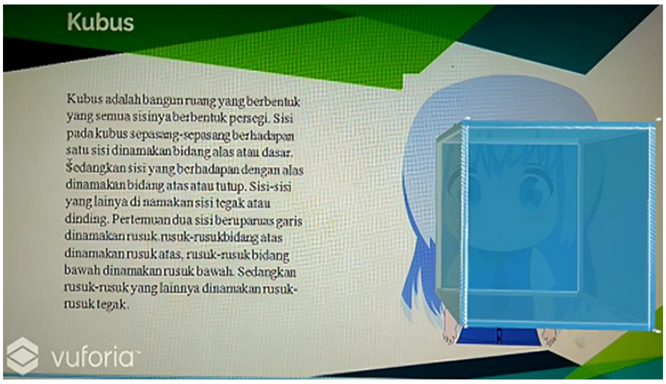


Figure 1. The display when the camera is highlighting the marker (Source: Authors' own elaboration)

The implementation of AR learning media reveals that students, who are learning three-dimensional objects, find the media helpful and can quickly understand the concept of space. They can see three-dimensional objects from various perspectives, including the front, side, back, top, and bottom parts of them. Students often struggle to locate the diagonal in a three-dimensional object, especially when it's located next to or behind the object. They struggle to imagine what the diagonal form is. However, with AR-based geometry media, students can freely rotate three-dimensional objects by simply moving the highlighted marker and rotating it until they find the desired part to view.

Observation Results of Students' Interactivity

Observation results show that students demonstrated noticeable engagement with the technology following the implementation of AR learning media. Throughout the teaching and learning process, we collected data on their interactive responses, focusing on several key indicators of interactivity. These indicators provide valuable insights into how students interacted with the AR media. The total interaction reflects the frequency with which students engaged with the AR tools, indicating how often they utilized the technology during lessons. Meanwhile, time of interaction measures the duration of these engagements, showing how long students actively interacted with the AR features. One could spend this time navigating, exploring, or completing tasks using the AR media. Additionally, the quality of interaction assesses the effectiveness of these interactions, focusing on how well students were able to achieve their learning goals through their engagement with the AR tools. This metric highlights not just the quantity of interaction, but also how meaningful and productive these interactions were in supporting student learning outcomes.

Table 3. Students' interactivity towards the use of AR geometry

Indicators	Percentage (%)				
	1st week	2nd week	3rd week	4th week	Average
Total interaction	65	70	73	74	70.5
Time of interaction	63	72	74	77	71.5
Quality of interaction	68	71	72	74	71.3
Response to the application	70	73	74	74	72.8
User interaction	65	70	72	73	70
Personalize of interaction	68	72	72	74	71.5
Impact of interaction	66	71	72	74	70.8
Responsivity	67	73	74	76	72.5
Customization	74	75	75	76	75.0
Collaboration	72	73	73	74	73.0
Average	68.0	72.0	73.1	74.674.6	71.9

The findings presented in **Table 3** illustrate the students' active engagement with the use of AR in their learning over a four-week period. The data is presented in percentage values (P%), which reflect the level of interaction based on various indicators. The average interaction across the four weeks is 71.9%, indicating that students had a generally positive response to AR-based learning.

Table 3 reveals several key trends in the interactivity of students with AR technology in learning environments. One notable finding is the continuous improvement in the total interaction, which started at 65% and increased to 74% by the final week. This indicates that as students became more comfortable with the technology, their overall engagement increased. The time of interaction and quality of interaction also showed similar upward trends, which is indicative of students dedicating more time to exploring the AR application and engaging with it in a more meaningful way. This aligns with previous studies that have shown the effectiveness of immersive technologies like AR in enhancing student engagement over time. The high average scores for customization and collaboration (75% and 73%, respectively) suggest that AR applications can effectively support both personalized learning and collaborative work among students. These are critical features in modern educational settings, where individualized learning paths and teamwork are increasingly emphasized. Interestingly, the response to the application and impact of interaction were consistently strong, averaging 72.8% and 70.8%, respectively. This suggests that students liked the AR environment and found it helpful for learning.

Furthermore, to evaluate the significance of differences in student interaction scores across the different weeks of the study, a one-way ANOVA analysis was conducted. This method was chosen to determine whether there were statistically significant variations in student interaction between the instruction weeks. Two important tests had to be done before the ANOVA could be done. The first was the Shapiro-Wilk normality test, which made sure that the data followed a normal distribution. The second was the homogeneity of variances test, which checked whether the variance between weeks was the same. These tests are essential for validating the assumptions of ANOVA and ensuring the accuracy and reliability of the results.

Table 4. Tests of normality

	Week	Shapiro-Wilk		
		Statistic	df	Sig.
Percentage (%)	1st	.960	10	.782
	2nd	.933	10	.475
	3rd	.855	10	.067
	4th	.794	10	.012

The data for the 1st, 2nd, and 3rd weeks can be considered normally distributed, while the data for the 4th week shows significant deviations from normality (**Table 4**). Given these results, while the majority of the weeks meet the assumption of normality, the 4th week does not, suggesting the need for cautious interpretation of parametric tests or the use of non-parametric alternatives. After this, we conducted a homogeneity of variance test to determine if the variances between weeks were equal (**Table 5**).

Based on the results of the homogeneity of variance test, where the significance value was found to be less than 0.05, it indicates that the assumption of homogeneity of variance was violated, meaning that the data is not homogeneous. Due to this, a standard ANOVA test would not be appropriate for post hoc analysis. To address this issue, a post hoc multiple comparison was carried out using the Games-Howell method. The Games-Howell test is particularly useful in situations where the assumption of equal variances is not met, as it does not require homogeneity of variance and can handle unequal sample sizes (Games & Howell, 1976). This test allows for a more reliable comparison of interaction scores between different weeks while accounting for the unequal variances observed in the data. By employing the Games-Howell method, we can better understand the significant differences between weeks in terms of student interaction with AR media, ensuring that the analysis is robust despite the violation of homogeneity (**Table 6**).

Table 5. Test of homogeneity of variances

		Levene statistics	df1	df2	Sig.
Percentage (%)	Based on mean	4.434	3	36	.009
	Based on median	4.246	3	36	.011
	Based on median and with adjusted df	4.246	3	20.053	.018
	Based on trimmed mean	4.444	3	36	.009

Table 6. Games-Howell post-hoc test

(I) Week	Mean	Standard deviation	(J) Week	Mean difference (I-J)	Standard error	Sig.	95% confidence interval	
							Lower bound	Upper bound
1st Week	67.80	3.393	2nd	-4.200*	1.181	.017	-7.68	-.72
			3rd	-5.300*	1.128	.003	-8.70	-1.90
			4th	-6.800*	1.145	.000	-10.22	-3.38
2nd Week	72.00	1.563	1st	4.200*	1.181	.017	.72	7.68
			3rd	-1.100	.605	.300	-2.83	.63
			4th	-2.600*	.636	.004	-4.41	-.79
3rd Week	73.10	1.101	1st	5.300*	1.128	.003	1.90	8.70
			2nd	1.100	.605	.300	-.63	2.83
			4th	-1.500	.530	.050	-3.00	.00
4th Week	74.60	1.265	1st	6.800*	1.145	.000	3.38	10.22
			2nd	2.600*	.636	.004	.79	4.41
			3rd	1.500	.530	.050	.00	3.00

Note. *The mean difference is significant at the 0.05 level

The results from **Table 6**, which presents the Games-Howell post-hoc test, reveal significant changes in student interaction scores between specific weeks. Significant differences were observed between the 1st week and the 2nd week (mean difference: -4.2, Sig. = 0.017), the 1st week and the 3rd week (mean difference: -5.3, Sig. = 0.003), and the 1st week and the 4th week mean difference: -6.8, Sig. = 0.000). This indicates substantial improvements in interaction scores over time. However, significant changes were also found between the 2nd week and the 4th week (mean difference: -2.6, Sig. = 0.004), and between the 3rd week and the 4th week (mean difference: -1.5, Sig. = 0.050). In contrast, no significant difference was detected between the 2nd week and the 3rd week (Sig. = 0.300), suggesting that the interaction level remained stable during this period.

Overall, the data shows that while there were no significant changes from the 2nd week to the 3rd week, there was a significant increase in interaction scores from the 1st week to the 2nd week, as well as from the 3rd week to the 4th week. Despite the absence of a significant leap between the 2nd and 3rd week, there is a clear trend of increasing interaction scores each week, reflecting an overall improvement in engagement.

Students' Responses After Using AR Geometry

This research uses a survey instrument to reveal students' responses after using AR geometry. The question categorizes feedback across several key components: usability, reliability, compatibility, interactivity, motivation, suitability of the field of study, visual appeal, and layout. Each component is assessed to gauge the effectiveness and reception of the AR geometry application in enhancing the learning experience. The scores obtained are compared to ideal benchmarks to determine the percentage of positive student responses. This evaluation aims to highlight the strengths and areas for improvement in AR geometry, offering insights into its overall impact on student engagement and learning outcomes in geometry.

Table 7 presents the students' responses to the use of AR geometry across various components, including usability, reliability, compatibility, interactivity, motivation, suitability, visual appeal, and layout. The usability component, which encompasses ease of use and comfort, received a score of 698 out of 888, yielding a percentage of 78.6%. This indicates that while the AR application was generally easy and comfortable to use, there is some room for improvement.

In the interactivity and motivation components, the AR application scored 858 out of 1,036, resulting in 82.8%. This high percentage suggests that the application effectively responds to user commands, enhances learning motivation, and is well-suited to the geometric materials being taught. The visual and layout components scored 495 out of 592, which corresponds to 83.6%. This score reflects the perception of the application's visual presentation and layout as attractive and user-friendly.

Overall, the AR application for learning geometry received positive feedback from students, with an 81.7% satisfaction rate. This suggests that students find the AR tool effective and engaging, although there is still potential for refinement in some areas to fully meet the ideal expectations.

Table 7. Student's responses to the AR geometry in learning

No	AR application component	Score	IS	P (%)
1	*Usability* • Application is easy to use without any difficulty • Application is comfortable to use *Reliability* • The application is not slow during use • The application does not experience errors when used *Compatibility* • The application can be used on other smartphones • Applications can be installed on other smartphones	698	888	78.6
2	*Interactivities* • The application responds to everything the user commands • Responses in the application are easy to understand • Responses in the application help convey learning material well *Motivation* • Applications provide a new atmosphere in learning • Applications increase enthusiasm for learning *Suitability of field of study* • Applications increase knowledge • Application according to geometric materials	858	1,036	82.8
3	*Visual* • The application is presented attractively • The type of font used by the application is clearly legible *Layout* • Application navigation buttons are easy to understand • Attractive app navigation buttons	495	592	83.6
Total		2,051	2,516	81.7

DISCUSSION

Students' Interactivity in Using AR Geometry

The results showed a significant increase in student interactivity with AR-based learning media, as evidenced by the continuous improvement in interaction scores over the four weeks. This increase in engagement aligns with studies by Capone and Lepore (2020) and Videnovik et al. (2020), who found that AR significantly boosts student involvement by providing immersive and interactive learning experiences. The ability to interact with three-dimensional objects in real time enables students to explore geometric figures from multiple perspectives, deepening their understanding of spatial relationships and properties.

A notable finding was the steady improvement in total interaction, which started at 65% and increased to 74% by the final week. This trend suggests that as students became more comfortable with AR technology, their overall engagement increased. This observation is consistent with prior research by Videnovik et al. (2020) and Baxter and Hainey (2024), which found that immersive technologies like AR can significantly boost student engagement over time. The gradual increase in interaction scores indicates that while students needed some time to adapt to the new technology, once familiar, they interacted more frequently and effectively with the AR applications.

The overwhelmingly positive responses from students to the AR applications in geometry underscore the transformative potential of AR in educational settings. The consistent strength of the response to the application (72.8%) and the impact of interaction (70.8%) suggest that students not only engaged well with the AR environment but also found it significantly beneficial to their learning processes. This finding is in line with Syawaludin and Rintayati (2019) and Karagozlu (2018), who demonstrated that AR enhances students' motivation and learning experiences by making abstract concepts more tangible and comprehensible. The ability of AR to make complex geometric concepts more accessible and engaging highlights its power as a learning media.

We observed improvements in both the time and quality of interaction, indicating that students dedicated more time to explore the AR application and engaged with it more meaningfully as the weeks progressed. This finding aligns with Capone and Lepore (2020), who reported that AR media enhances student involvement by providing an interactive and immersive learning experience. Students found the technology engaging and motivated to spend more time understanding and manipulating the geometric figures, as evidenced by the increased time they spent on AR activities.

High average scores for customization (75%) and collaboration (73%) indicate that AR applications can effectively support both personalized learning and collaborative work among students. These features are critical in modern educational settings, where individualized learning paths and teamwork are increasingly emphasized. Research by Wang (2020) and Johnson et al. (2014) supports this finding, highlighting how AR can facilitate personalized learning experiences and foster collaboration by allowing students to interact with learning materials in ways that suit their individual learning styles and by promoting group activities. This study's findings corroborate Hwang et al. (2020), which showed significant improvements in geometric reasoning and spatial estimation abilities among students using technology-supported learning materials.

Students' Responses in Using AR Geometry

The satisfaction expressed by students regarding the AR materials, noting their ease of use and effectiveness in concretizing abstract concepts, aligns with the research of Dunleavy et al. (2009). Dunleavy et al. emphasized how AR simulations and interactive games drive active participation and interaction in learning. The high scores for usability (78.6%) suggest that, although students generally found the AR application easy to navigate, there is still room for improvement. This finding supports Dutta et al. (2021), who stressed the importance of user-friendly interfaces in educational AR applications. Ensuring the reliability of the application, with no significant delays or errors reported, is crucial for maintaining student engagement and preventing frustration, as highlighted by Sun et al. (2008).

The high scores for interactivity and motivation (82.8%) indicate that the AR application effectively engaged students and enhanced their enthusiasm for learning geometry. This aligns with the findings of Di Serio et al. (2013) and Videnovik et al. (2020), who demonstrated that AR significantly boosts student motivation and engagement by making learning more interactive and enjoyable. The ability of AR to respond to user commands and facilitate a dynamic learning environment plays a crucial role in maintaining student interest and promoting active participation, as supported by the research of Chiang et al. (2014).

The application's high suitability for teaching geometric concepts suggests that AR is particularly effective for subjects requiring spatial visualization and manipulation. This is corroborated by Cheng and Tsai (2013), who found that AR applications are highly effective in geometry education, where visualizing three-dimensional structures is essential for understanding. The visual appeal and layout of the AR application received an 83.6% score, indicating that students found it visually attractive and easy to navigate. This finding is consistent with Lisowski et al. (2023) and Wang et al. (2014), who noted that well-designed visual elements and intuitive layouts are crucial for enhancing user experience and facilitating effective learning. The positive reception of the AR tool is likely due to its attractive presentation and clear navigation buttons, aligning with the principles of effective educational technology design outlined by Hilfert and König (2016).

The overall satisfaction rate of 81.7% reflects the positive impact of the AR geometry application on student engagement and learning outcomes. This finding is consistent with prior research by Ibáñez and Delgado-Kloos (2018) and Mystakidis et al. (2022), who reported that AR applications significantly enhance learning experiences and outcomes across various educational contexts. However, the data also suggest areas for improvement, particularly in usability. Enhancing the user interface and functionality could further increase student satisfaction and effectiveness.

Future Implications and Recommendations

The findings from the analysis of students' interactivity and responses to the AR geometry application highlight several important implications for the future of educational technology in geometry and beyond. The continuous improvement in student interaction and high levels of engagement suggest that AR has the potential to revolutionize the way geometric concepts are taught, making abstract ideas more tangible and accessible. As students demonstrated increased comfort and effectiveness in using AR technology over time, it is evident that incorporating such interactive tools into the curriculum can significantly enhance learning outcomes. This aligns with existing literature that emphasizes the importance of interactive and immersive learning experiences in fostering deeper understanding and retention of complex concepts.

Given the positive student feedback and the substantial increase in engagement, it is recommended that educators and institutions consider wider implementation of AR technologies across various subjects. AR can be particularly beneficial in areas requiring spatial visualization and manipulation, such as science, engineering, and art. To maximize the potential of AR in education, it is essential to provide adequate training for teachers to integrate these tools effectively into their teaching practices. Additionally, developing user-friendly and reliable AR applications tailored to the curriculum can further enhance student learning experiences.

Future research should focus on exploring the long-term effects of AR on student learning and engagement. It is important to investigate how sustained use of AR technology impacts student performance, motivation, and overall attitude towards learning. Expanding the scope of AR applications to include other subjects and diverse student populations can provide a more comprehensive understanding of its educational benefits. Furthermore, addressing the areas for improvement identified in the study, particularly in usability, can lead to the development of more refined and effective AR tools that meet the needs and preferences of students.

Collaboration between educational institutions, technology developers, and policymakers is crucial to ensuring the successful integration of AR in education. Providing the necessary resources and infrastructure, along with ongoing support and training for educators, can facilitate the widespread adoption of AR technology. By leveraging the strengths of AR to create more engaging and interactive learning environments, educators can better cater to the diverse learning styles and needs of students, ultimately enhancing the overall quality of education. The positive outcomes observed in this study underscore the transformative potential of AR in education. By continuing to explore and refine the use of AR in teaching and learning, we can pave the way for more innovative, effective, and enjoyable educational experiences for students.

CONCLUSION

This study contributes to the growing body of literature on the benefits of AR in education, particularly in geometry learning. The significant increase in student interactivity and positive responses to AR geometry applications underscores the potential of AR to transform traditional teaching methods and enhance student engagement and understanding of complex concepts. By providing an interactive and immersive learning environment, AR can help students better grasp abstract ideas, making learning more enjoyable and effective.

Author contributions: DR: wrote the paper, collected the data, performed analysis, and conceived and designed the analysis; **SSAR, HZ, & MOR:** wrote the paper and performed the analysis, proofreading, and grammatical check. All authors have agreed with the results and conclusions.

Funding: This study was supported by the LPDP, Ministry of Finance, Republic of Indonesia.

Ethical statement: The authors stated that the study adhered to the highest ethical practices. In relation to the conduct of the research, the authors have obtained permission from the related institutions. The privacy and anonymity of the research participants were strictly observed. Written informed consents were obtained from the participants.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

REFERENCES

Alkhateeb, M. A., & Al-Duwairi, A. M. (2019). The effect of using mobile applications (GeoGebra and Sketchpad) on the students' achievement. *International Electronic Journal of Mathematics Education, 14*(3), 523-533. https://doi.org/10.29333/iejme/5754

Amir, Z., & Sari, N. (2018). The development of learning media based on visual, auditory, and kinesthetic (VAK) approach to facilitate students' mathematical understanding ability. *Journal of Physics: Conference Series, 1028*, Article 012129. https://doi.org/10.1088/1742-6596/1028/1/012129

Arena, F., Collotta, M., Pau, G., & Termine, F. (2022). An overview of augmented reality. *Computers, 11*(2), Article 28. https://doi.org/10.3390/computers11020028

Azuma, R. T. (1997). A survey of augmented reality. *Presence: Teleoperators & Virtual Environments, 6*(4), 355-385. https://doi.org/10.1162/pres.1997.6.4.355

Baxter, G., & Hainey, T. (2024). Using immersive technologies to enhance the student learning experience. *Interactive Technology and Smart Education, 21*(3), 403-425. https://doi.org/10.1108/ITSE-05-2023-0078

Bishop, A. J. (1980). Spatial abilities and mathematics education–A review. *Educational Studies in Mathematics, 11*(3), 257-269. https://doi.org/10.1007/BF00697739

Bülthoff, H. H., Edelman, S. Y., & Tarr, M. J. (1995). How are three-dimensional objects represented in the brain?. *Cerebral Cortex, 5*(3), 247-260. https://doi.org/10.1093/cercor/5.3.247

Büyüköztürk, S., Kılıç Cakmak, E., Akgün, O. E., Karadeniz, S., & Demirel, F. (2008). *Bilimsel araştırma yöntemleri* [Scientific research methods]. Pegem Publishing.

Cao, M. (2018). *An examination of three-dimensional geometry in high school curricula in the US and China* [PhD thesis, Columbia University].

Capone, R., & Lepore, M. (2020). Augmented reality to increase interaction and participation: A case study of undergraduate students in mathematics class. In *Proceedings of the 7th International Conference on Augmented Reality, Virtual Reality, and Computer Graphics* (pp. 185-204). Springer. https://doi.org/10.1007/978-3-030-58468-9_15

Chang, K. E., Wu, L. J., Lai, S. C., & Sung, Y. T. (2016). Using mobile devices to enhance the interactive learning for spatial geometry. *Interactive Learning Environments, 24*(4), 916-934. https://doi.org/10.1080/10494820.2014.948458

Cheng, K. H., & Tsai, C. C. (2013). Affordances of augmented reality in science learning: Suggestions for future research. *Journal of Science Education and Technology, 22*, 449-462. https://doi.org/10.1007/s10956-012-9405-9

Cheng, K. H., & Tsai, C. C. (2019). A case study of immersive virtual field trips in an elementary classroom: Students' learning experience and teacher-student interaction behaviors. *Computers & Education, 140*, Article 103600. https://doi.org/10.1016/j.compedu.2019.103600

Chiang, T. H., Yang, S. J., & Hwang, G. J. (2014). Students' online interactive patterns in augmented reality-based inquiry activities. *Computers & Education, 78*, 97-108. https://doi.org/10.1016/j.compedu.2014.05.006

Clements, D. H., & Battista, M. T. (1992). Geometry and spatial reasoning. In D. A. Grouws (Ed.), *Handbook of research on mathematics teaching and learning: A project of the National Council of Teachers of Mathematics* (pp. 420-464). Macmillan Library Reference.

Daniela, L. (2020). *New perspectives on virtual and augmented reality*. Routledge. https://doi.org/10.4324/9781003001874

Di Paola, F., Pedone, P., & Pizzurro, M. R. (2013). Digital and interactive learning and teaching methods in descriptive geometry. *Procedia-Social and Behavioral Sciences, 106*, 873-885. https://doi.org/10.1016/j.sbspro.2013.12.100

Di Serio, Á., Ibáñez, M. B., & Kloos, C. D. (2013). Impact of an augmented reality system on students' motivation for a visual art course. *Computers & Education, 68*, 586-596. https://doi.org/10.1016/j.compedu.2012.03.002

Dunleavy, M., Dede, C., & Mitchell, R. (2009). Affordances and limitations of immersive participatory augmented reality simulations for teaching and learning. *Journal of Science Education and Technology, 18*, 7-22. https://doi.org/10.1007/s10956-008-9119-1

Dutta, R., Mantri, A., Singh, G., Kumar, A., & Kaur, D. P. (2021). Evaluating usability of mobile augmented reality system for enhancing the learning experience. In *Proceedings of the 6th International Conference on Image Information Processing* (pp. 180-185). IEEE. https://doi.org/10.1109/ICIIP53038.2021.9702603

Games, P. A., & Howell, J. F. (1976). Pairwise multiple comparison procedures with unequal n's and/or variances: A Monte Carlo study. *Journal of Educational Statistics, 1*(2), 113-125. https://doi.org/10.3102/10769986001002113

Glasnovic Gracin, D. (2018). Requirements in mathematics textbooks: A five-dimensional analysis of textbook exercises and examples. *International Journal of Mathematical Education in Science and Technology, 49*(7), 1003-1024. https://doi.org/10.1080/0020739X.2018.1431849

Hilfert, T., & König, M. (2016). Low-cost virtual reality environment for engineering and construction. *Visualization in Engineering, 4*, Article 2. https://doi.org/10.1186/s40327-015-0031-5

Hwang, W. Y., Zhao, L., Shadiev, R., Lin, L. K., Shih, T. K., & Chen, H. R. (2020). Exploring the effects of ubiquitous geometry learning in real situations. *Educational Technology Research and Development, 68*, 1121-1147. https://doi.org/10.1007/s11423-019-09730-y

Ibáñez, M. B., & Delgado-Kloos, C. (2018). Augmented reality for STEM learning: A systematic review. *Computers & Education, 123*, 109-123. https://doi.org/10.1016/j.compedu.2018.05.002

Ibili, E. M. I. N., & Sahin, S. A. M. I. (2015). The effect of augmented reality assisted geometry instruction on students' achievement and attitudes. *Teaching Mathematics and Computer Science, 13*(2), https://doi/177-193.10.5485/TMCS.2015.0392

Jelatu, S., & Ardana, I. (2018). Effect of GeoGebra-aided REACT strategy on understanding of geometry concepts. *International Journal of Instruction, 11*(4), 325-336. https://doi.org/10.12973/iji.2018.11421a

Johnson, D. W., Johnson, R. T., & Smith, K. A. (2014). Cooperative learning and individual student achievement in secondary schools. In J. E. Pedersen, & A. D. Digby (Eds.), *Secondary schools and cooperative learning* (pp. 3-54). Routledge. https://doi.org/10.4324/9781315047010-7

Karagozlu, D. (2018). Determination of the impact of augmented reality application on the success and problem-solving skills of students. *Quality & Quantity, 52*(5), 2393-2402. https://doi.org/10.1007/s11135-017-0674-5

Khan, T., Johnston, K., & Ophoff, J. (2019). The impact of an augmented reality application on learning motivation of students. *Advances in Human-Computer Interaction*. https://doi.org/10.1155/2019/7208494

Lisowski, D., Ponto, K., Fan, S., Probst, C., & Sprecher, B. (2023). Augmented reality into live theatrical performance. In A. Y. C. Nee, & S. K. Ong (Eds.), *Springer handbook of augmented reality* (pp. 433-450). Springer. https://doi.org/10.1007/978-3-030-67822-7_18

Malizar, & Johar, R. (2021). Examining students' intention to use augmented reality in a project-based geometry learning environment. *International Journal of Instruction, 14*(2), 773-790. https://doi.org/10.29333/iji.2021.14243a

Maqoqa, T. (2024). An exploration of learners' understanding of Euclidean geometric concepts: A case study of secondary schools in the OR Tambo Inland District of the Eastern Cape. *E-Journal of*

Humanities, Arts and Social Sciences, 5(5), 658-675. https://doi.org/10.38159/ehass.2024557

Müller, F. A., & Wulf, T. (2020). Technology-supported management education: A systematic review of antecedents of learning effectiveness. *International Journal of Educational Technology in Higher Education, 17*(1), Article 47. https://doi.org/10.1186/s41239-020-00226-x

Mystakidis, S., Christopoulos, A., & Pellas, N. (2022). A systematic mapping review of augmented reality applications to support STEM learning in higher education. *Education and Information Technologies, 27*(2), 1883-1927. https://doi.org/10.1007/s10639-021-10682-1

Nindiasari, H., Pranata, M. F., Sukirwan, S., Sugiman, S., Fathurrohman, M., Ruhimat, A., & Yuhana, Y. (2024). The use of augmented reality to improve students' geometry concept problem-solving skills through the STEAM approach. *Infinity Journal, 13*(1), 119-138. https://doi.org/10.22460/infinity.v13i1.p119-138

Pashler, H., McDaniel, M., Rohrer, D., & Bjork, R. (2008). Learning styles: Concepts and evidence. *Psychological Science in the Public Interest, 9*(3), 105-119. https://doi.org/10.1111/j.1539-6053.2009.01038.x

Pavlovicova, G., & Zahorska, J. (2015). The attitudes of students to the geometry and their concepts about square. *Procedia-Social and Behavioral Sciences, 197*, 1907-1912. https://doi.org/10.1016/j.sbspro.2015.07.253

Permatasari, G. I., & Andayani, S. (2021). Teachers' challenges in teaching geometry using augmented reality learning media. *AKSIOMA: Jurnal Program Studi Pendidikan Matematika, 10*(4), Article 2159. https://doi.org/10.24127/ajpm.v10i4.3889

Potkonjak, V., Gardner, M., Callaghan, V., Mattila, P., Guetl, C., Petrović, V. M., & Jovanović, K. (2016). Virtual laboratories for education in science, technology, and engineering: A review. *Computers & Education, 95*, 309-327. https://doi.org/10.1016/j.compedu.2016.02.002

Prabowo, A., Anggoro, R. P., Astuti, D., & Fahmi, S. (2017). Interactive multimedia-based teaching material for 3-dimensional geometry. *Journal of Physics: Conference Series, 943*, Article 012047. https://doi.org/10.1088/1742-6596/943/1/012047

Price, S., Yiannoutsou, N., & Vezzoli, Y. (2020). Making the body tangible: Elementary geometry learning through VR. *Digital Experiences in Mathematics Education, 6*(2), 213-232. https://doi.org/10.1007/s40751-020-00071-7

Pujiastuti, H., & Haryadi, R. (2024). The effectiveness of using augmented reality on the geometry thinking ability of junior high school students. *Procedia Computer Science, 234*, 1738-1745. https://doi.org/10.1016/j.procs.2024.03.180

Puloo, M. M. L., Juniati, D., & Wijayanti, P. (2018). Visualization profile of junior high school students in solving geometry problems viewed from gender differences. *Journal of Physics: Conference Series, 1108*, 012063. https://doi.org/10.1088/1742-6596/1108/1/012063

Ramadhan, M. O., Rohendi, D., Handayani, M. N., & Ilhamdaniah, I. (2024). Rethinking learning media and ICT literacy courses for future vocational teachers: Ensuring quality in learning media. In *Proceedings of the 9th International STEM Education Conference* (pp. 1-9). IEEE. https://doi.org/10.1109/iSTEM-Ed62750.2024.10663165

Ratnasari, D., Wahyu, K., & Mahfudy, S. (2018). Teachers' old-fashioned classroom practices: A pitfall on the use of digital technology in mathematics teachings. *Beta: Jurnal Tadris Matematika, 11*(2), 114-130. https://doi.org/10.20414/betajtm.v11i2

Rezat, S., Fan, L., & Pepin, B. (2021). Mathematics textbooks and curriculum resources as instruments for change. *ZDM–Mathematics Education, 53*(6), 1189-1206. https://doi.org/10.1007/s11858-021-01309-3

Rohendi, D., Septian, S., & Sutarno, H. (2018). The use of geometry learning media based on augmented reality for junior high school students. *IOP Conference Series: Materials Science and Engineering, 306*, Article 012029. https://doi.org/10.1088/1757-899X/306/1/012029

Rossano, V., Lanzilotti, R., Cazzolla, A., & Roselli, T. (2020). Augmented reality to support geometry learning. *IEEE Access, 8*, 107772-107780. https://doi.org/10.1109/ACCESS.2020.3000990

Schutera, S., Schnierle, M., Wu, M., Pertzel, T., Seybold, J., Bauer, P., Teutscher, D., Raedle, M., Heß-Mohr, N., Röck, S., & Krause, M. J. (2021). On the potential of augmented reality for mathematics teaching with the application cleARmaths. *Education Sciences, 11*(8), Article 368. https://doi.org/10.3390/educsci11080368

Sorby, S. A., & Panther, G. C. (2020). Is the key to better PISA math scores improving spatial skills? *Mathematics Education Research Journal, 32*(2), 213-233. https://doi.org/10.1007/s13394-020-00328-9

Stieff, M., Bateman, R. C., & Uttal, D. H. (2005). Teaching and learning with three-dimensional representations. In J. K. Gilbert (Ed.), *Visualization in science education. Models and modeling in science education, vol 1* (pp. 93-120). Springer. https://doi.org/10.1007/1-4020-3613-2_7

Su, Y. S., & Wu, S. Y. (2021). Applying data mining techniques to explore user behaviors and watching video patterns in converged IT environments. *Journal of Ambient Intelligence and Humanized Computing*. https://doi.org/10.1007/s12652-020-02712-6

Sun, P. C., Tsai, R. J., Finger, G., Chen, Y. Y., & Yeh, D. (2008). What drives a successful e-learning? An empirical investigation of the critical factors influencing learner satisfaction. *Computers & Education, 50*(4), 1183-1202. https://doi.org/10.1016/j.compedu.2006.11.007

Syawaludin, A., & Rintayati, P. (2019). Development of augmented reality-based interactive multimedia to improve critical thinking skills in science learning. *International Journal of Instruction, 12*(4), 331-344. http://dx.doi.org/10.29333/iji.2019.12421a

The Common Core State Standards Initiative. (2022). *The common core state standards for mathematics*. https://learning.ccsso.org/wp-content/uploads/2022/11/ADA-Compliant-Math-Standards.pdf

Tomiczková, S., & Lávička, M. (2013). Computer-aided descriptive geometry teaching. *Computers in the Schools, 30*(1-2), 48-60. https://doi.org/10.1080/07380569.2013.764480

Trivedi, P. (2024). Immersive learning's promise: The educational potential of augmented and virtual reality. In V. A. Devi, W. Singh, & Y. Kumar (Eds.), *Augmented reality and virtual reality in special education* (pp. 91-102). Wiley. https://doi.org/10.1002/9781394167586.ch4

Tsao, Y. L. (2017). Pre-service elementary school teachers' attitude towards geometry. *US-China Education Review B, 7*(1), 15-22. https://doi.org/10.17265/2161-6248/2017.01.002

Videnovik, M., Trajkovik, V., Kiønig, L. V., & Vold, T. (2020). Increasing quality of learning experience using augmented reality educational games. *Multimedia Tools and Applications, 79*(33), 23861-23885. https://doi.org/10.1007/s11042-020-09046-7

Vorstenbosch, M. A., Klaassen, T. P., Donders, A. R. T., Kooloos, J. G., Bolhuis, S. M., & Laan, R. F. (2013). Learning anatomy enhances spatial ability. *Anatomical Sciences Education, 6*(4), 257-262. https://doi.org/10.1002/ase.1346

Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology, 101*(4), 817. https://doi.org/10.1037/a0016127

Wang, Y. H. (2020). Integrating games, e-books and AR techniques to support project-based science learning. *Educational Technology & Society, 23*(3), 53-67. https://www.jstor.org/stable/26926426

Yunianta, T. N. H., Suryadi, D., Dasari, D., & Herman, T. (2023). Textbook praxeological-didactical analysis: Lessons learned from the Indonesian mathematics textbook. *Journal on Mathematics Education, 14*(3), 503-524. https://doi.org/10.22342/jme.v14i3.pp503-524

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