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Personalization of Interactive Teaching Materials Supported by Augmented Reality: Potentials vs Obstacles in 3D Geometry Learning

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ABSTRACT

Although extensive publications have been conducted on the implementation of Augmented Reality (AR) technology in geometry learning, there is still limited exploration of potentials and obstacles associated with Interactive Teaching Materials Assisted by Augmented Reality (ITMA-AR) in 3D geometry learning. Therefore, this study aimed to investigate potentials and obstacles of ITMA-AR in geometry learning in schools using an explanatory sequential design (ESD). A total of 48 students and three high school mathematics teachers voluntarily participated in learning facilitated with ITMA-AR. Data were collected through interviews, observations, as well as tests, and further analyzed both quantitatively and qualitatively. The results showed that ITMA-AR possessed significant potentials to improve 3D geometry learning but also faced several obstacles. The study identified two main areas of potential namely internal and external. Internally, AR provided immersive visualization and motivated student engagement by enabling direct interaction with 3D objects in a virtual environment. Externally, it enhanced students' understanding of 3D geometry concepts, improved the visualization skills, and increased motivation to learn. The study also uncovered several barriers to effective implementation, including suboptimal application performance, hardware compatibility issues, and limited student access to ITMA-AR. The implications of these results suggested a need for curriculum revision, investment in technology infrastructure, and comprehensive teacher training to address these obstacles effectively.

KEYWORDS

Explanatory sequential design; ITMA-AR; potential and obstacles; 3D geometry learning.

INTRODUCTION

The landscape of teaching and learning is experiencing rapid transformation due to technological advancements (Alam, 2021; Isnawan et al., 2024; Malik, 2018). The advancements are revolutionizing the way education is delivered and received, making it more accessible and efficient. Teachers and students can further access a wide range of educational technology products that serve as valuable learning resources (Delgado et al., 2015; Mosia & Matabane, 2022). These tools include interactive whiteboards, web resources, educational software, online courses, and virtual reality (VR) experiences, all designed to enhance the learning process (Sudirman et al., 2025).

Educational technology products not only facilitate dynamic teaching but also create interactive and engaging learning environments (Facer & Sandford, 2010; Haddad & Draxler, 2002; Orakova et al., 2024). For instance, gamified learning platforms can make lessons more enjoyable and motivate students to participate actively. These technologies also enable more personalized learning by allowing educators to customize the teaching methods to the individual needs of each student (Alamri et al., 2021; FitzGerald et al., 2018; Mpiti et al., 2023). The personalized method addresses diverse learning styles, preferences, interests, and paces, ensuring that no student is left behind.

Moreover, the use of technology in education fosters collaboration among students, enhancing social skills and teamwork (Blau et al., 2020; Lawlor et al., 2018). Collaborative tools such as online discussion forums, group projects, peer-to-peer collaboration, and peer review systems motivate students to work together, interact, share ideas, and learn from one another (Noviyanti et al., 2025). This collaborative learning environment not only improves knowledge, skills, attitudes, and academic performance but also prepares students for the team-oriented nature of the modern workplace.

Learning and teaching mathematics, particularly geometric concepts present significant challenges. Sudirman et al. (2023) further identified issues related to the representation of 3D geometry which often confused students. Additionally, challenges exist in learning surface area and volume measurement of 3D geometric shapes (Huang & Wu, 2019; Özerem, 2012; Tan-Sisman & Aksu, 2016). Students' inability to visualize the spatial structure of geometric elements often hinders comprehension (Baiduri et al., 2020; Gal & Linchevski, 2010; Sudirman et al., 2023; Susilawati et al., 2017). This difficulty in visualization can lead to frustration and loss of motivation, specifically when students encounter more complex geometric concepts (Age & Machaba, 2024; Nguyen, 2019).

These difficulties affect not only students but also teachers, who struggle to effectively teach geometric concepts (Dobbins et al., 2014). A lack of suitable resources and teaching aids correlated with students' needs and curriculum demands further exacerbates these challenges. In response, publications have explored various innovative methods such as ethnomathematics (Bantaika et al., 2025; Rodríguez-Nieto et al., 2025; Sudirman et al., 2024; Sukestiyarno et al., 2023; Sunzuma & Maharaj, 2019; Verner et al., 2019) and Realistic Mathematics Education which connects mathematics with real-life contexts (Alim et al., 2020; Aksu & Colak, 2021; Vazila et al., 2020). These methods aim to make learning more meaningful and engaging, thereby enhancing students' understanding and retention of geometric concepts.

Publications have also attempted to overcome difficulties in understanding geometry through various technological products. For example, Birgin & Topuz (2021), Kusumah et al. (2020), and Uwurukundo et al. (2022; 2023) adopted GeoGebra to teach 3D geometry and support improvements in both cognitive and affective learning. GeoGebra, a dynamic mathematics software allows students to visualize and manipulate geometric shapes, making abstract ideas more concrete, accessible, and understandable (Basri et al., 2025). Similarly, Latif et al. (2020) and Miatun (2018) used Cabri 3D in geometry learning to help students improve spatial abilities. This interactive geometry software allows students to construct and explore 3D shapes, enhancing the ability to visualize and understand spatial relationships. The tool is effective in helping students understand complex geometric concepts by providing a hands-on learning experience. Fonna et al. (2019), Kariadinata et al. (2019), and Mayasari et al. (2020) applied Wingeom to improve students' spatial representation skills. Wingeom is another powerful tool that allows students to create and manipulate geometric figures, thereby improving the understanding of geometric properties and relationships. The use of this software has been shown to significantly enhance students' spatial reasoning skills, which are crucial for success in geometry.

İbili et al. (2020), Gargrish et al. (2021), Rohendi & Wihardi (2020), and Sudirman et al. (2020; 2021; 2022) explored the use of Augmented Reality (AR) in aiding 3D geometric objects and further improve students' understanding of geometry. AR technology overlays digital information in the real world, allowing students to interact with 3D geometric shapes in a more immersive method. This method further enhances students' comprehension of geometric concepts by providing a more intuitive and interactive learning experience. Similarly, Su et al. (2022) used VR in geometry learning to offer students an immersive environment where geometric shapes could be explored and manipulated. VR further provides a fully immersive experience that can make learning more engaging and effective, particularly for complex subjects such as geometry (Pahmi et al., 2024).

Despite the promising outcomes, few studies have specifically focused on examining potentials and obstacles of AR implementation in geometry classrooms from practical and school infrastructure perspectives. Among interactive tools frequently used in geometry learning (Sudirman et al., 2020; 2021; 2022), AR stands out for its potential to help students visualize abstract geometric concepts more tangibly (Demitriadou et al., 2020; İbili et al., 2020; Reddy & Singaravelu, 2020). By blending digital content with real-world settings, AR creates a more immersive and comprehensive learning experience (Papanastasiou et al., 2019), leading to higher engagement and deeper understanding (Ibáñez et al., 2018).

Although AR offers various benefits in geometry learning including increased engagement and understanding of 3D geometry concepts, obstacles such as cost and technical skills remain significant challenges. Limited studies also exist on the application of AR in mathematics education within the Indonesian context. Therefore, this study aims to fill the literature gap by examining potentials and obstacles of using ITMA-AR in 3D geometry learning through an explanatory sequential design (ESD). The questions guiding this study include the following.

- Does the use of ITMA-AR significantly improve students' understanding of 3D geometry concepts?
- What potential uses of ITMA-AR exist in improving students' understanding of 3D geometry?
- What obstacles do teachers and students face when using ITMA-AR?

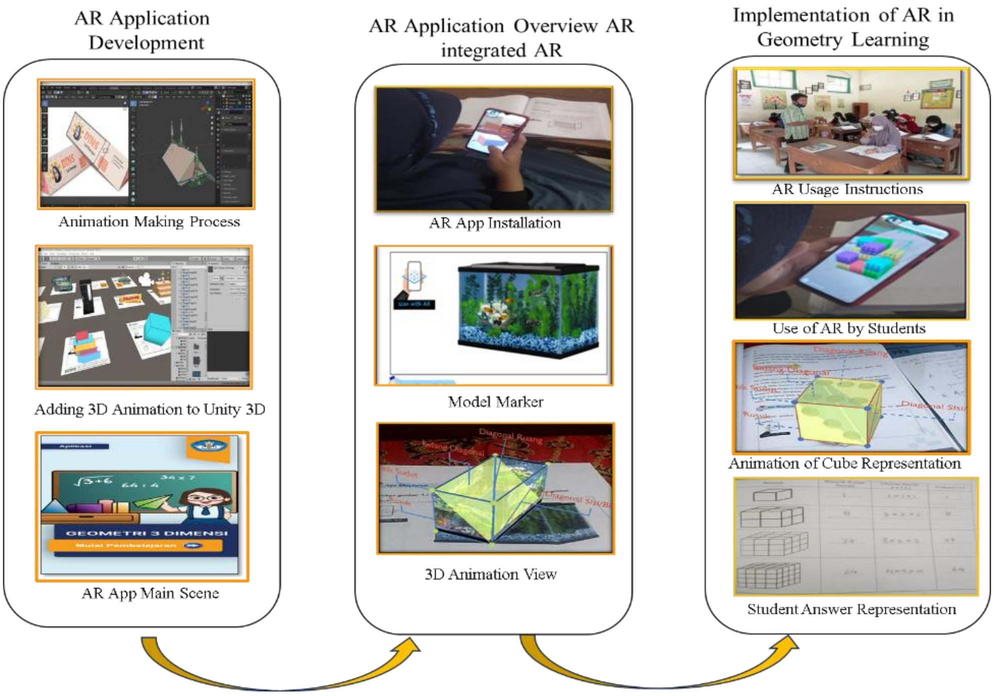
METHODS

Study Design

This study used an ESD which was part of the Mixed Methods including two sequential phases namely quantitative and qualitative (Creswell & Clark, 2018). In the first phase, the study adopted an experimental method to evaluate the effectiveness of interactive teaching materials assisted by ITMA-AR in 3D geometry learning. ITMA-AR referred to a learning material that integrated AR technology to help students understand geometric concepts through 3D visualizations. By using mobile devices, students were able to view and interact directly with 3D geometric models from the textbooks. The process of using ITMA-AR consisted of several stages as showed in Figure 1.

Figure 1.

Stages of AR Application Usage



The first stage included creating animations and 3D models which were then integrated into the Unity 3D platform. At this stage, geometric models were designed, animated, and configured to operate within the AR environment. Physical markers usually geometric shapes printed on paper were also created. These markers served to trigger the display of 3D models when viewed through the AR application. Once the application was developed, students installed it on the mobile devices. When the device's camera was pointed at a marker, the corresponding 3D model appeared on the screen and could be viewed from multiple angles. In the classroom, the teacher provided guidance on how to use the AR app and assisted students in interacting with the models. Students explored geometric shapes interactively with tablets or smartphones. This method helped the students helped the students better understand geometric concepts by visualizing and manipulating the models in three-dimensional space.

In the second phase, the study adopted a qualitative method using Grounded Theory (GT) to explore and develop themes based on the experiences of teachers and students after using ITMA-AR. As stated by Birks and Mills (2022), GT offered flexibility for understanding complex experiences without the constraints of a predetermined conceptual framework. Before implementing ITMA-AR in the classroom, the author conducted interviews with six mathematics teachers (two each from Grades VII, VIII, and IX) from a public junior high school in Indramayu, West Java, Indonesia. These interviews aimed to identify the challenges teachers faced in teaching geometry. The results showed that four teachers used PowerPoint as a visualization tool while the remaining two relied solely on school textbooks, outlining the limited availability of interactive resources to support students' conceptual understanding of geometry.

Study Participants

The participants in this study consisted of two eighth-grade mathematics teachers and 48 eighth-grade students from classes VIII-B and VIII-E at a public junior high school located in Indramayu Regency, West Java Province, Indonesia. The students were junior high school students, not college-level and the data were collected from both students and teachers. The two teachers included a 38-year-old male and a 34-year-old female, both of whom had teaching experience in geometry and served as key informants. The teachers provided valuable insights into the implementation and development of ITMA-AR in 3D geometry instruction.

In this study, the author also acted as the key instrument which was common in qualitative analysis. The term "key informants" referred to the author's direct participation in data collection, interpretation, and validation through classroom observations, in-depth interviews, documentation of learning activities, and reflective practices. However, this did not imply that no other instruments were used. Additional supporting instruments included classroom observation sheets, interview guides for both teachers and students, worksheets, documentation (photos/videos), and pre- and post-tests to measure students' geometry comprehension.

Student participants were selected based on three main considerations namely the readiness to engage in AR-based learning, the relevance of the developed learning materials, and the availability of necessary devices and supporting facilities. Class VIII-B consisted of 23 students (17 females and 6 males) while class VIII-E comprised 25 students (15 females and 10 males). All students were between 13 and 14 years old.

Before the implementation of the learning activities, informed consent was obtained from all 48 students, who voluntarily agreed to participate. Additionally, students received a technical orientation on how to use the ITMA-AR application and were given an overview of the AR-based learning process to ensure that the students were well-prepared to engage fully in the learning experience. The detailed characteristics of the student participants are presented in Table 1.

Table 1.

Student Characteristics

Grade	Total Students	Age	Gender
VIII B	23 students	13-14 years	17 females, 6 males
VIII E	25 students	13-14 years	15 females, 10 males
Total	48 students		

Data Collection

The data collection procedure in this study included three main instruments namely observation, interview, and test, each of which served a distinct purpose, followed different procedures, and produced various data. To ensure methodological rigor, all instruments were prepared in advance and were customized to the specific objectives of the study. Observations were also used to gain contextual insights into classroom dynamics while interviews were used to explore participants' perspectives in depth. Additionally, tests were conducted to quantitatively measure learning outcomes related to 3D geometry. The procedures for each method were detailed as follows.

a) Observations

Non-participatory classroom observations were conducted to capture the authentic learning atmosphere during the implementation of ITMA-AR. A structured observation guide was used to focus on specific aspects such as the integration of AR technology into the instructional process, the nature of teacher-student interactions, peer collaboration, and visible indicators of student engagement (e.g., enthusiasm, active participation, and cooperation). Observations were carried out across five sessions, allowing for a comprehensive and contextualized understanding of classroom dynamics without disrupting the flow of instruction. The data collected through observations consisted of field notes and descriptive narratives, which were later analyzed qualitatively to identify patterns and themes related to teaching and learning behaviors.

b) Interview, Record, and Transcript

Semi-structured interviews were conducted with two eighth-grade mathematics teachers and three students to explore the perceptions and experiences of using ITMA-AR. Separate interview guides were developed for teachers and students to ensure relevance and depth. Teachers were asked about personal experiences implementing ITMA-AR as it perceived benefits in enhancing student understanding and engagement, as well as obstacles such as technical difficulties and lack of training. Students were further asked to describe the learning experiences with AR, the influence of 3D visualizations on comprehension of geometry, motivation, and how the technology affected classroom interaction and collaboration. All interviews were audio-recorded, transcribed verbatim, and analyzed thematically. Data saturation was reached through a step-by-step interview process, ensuring that recurring insights were adequately captured.

c. Test to Produce Scores

To evaluate students' learning outcomes, pre- and post-tests were administered before and after the ITMA-AR intervention. These tests were designed to measure three key dimensions of 3D geometry competence namely.

(a) Representation—students' ability to visualize and represent 3D objects.

(b) Spatial structure—the understanding of spatial relationships within geometric figures.

(c) Measurement—the ability to calculate surface area and volume.

The test consisted of five open-ended questions and was reviewed by mathematics education experts to ensure content validity, construct clarity, and reliability.

Data Analysis

To assess potential of ITMA-AR in enhancing students' understanding of 3D geometry concepts, this study adopted a mixed-methods with an ESD. In this design, the quantitative phase was conducted first to examine the impact of ITMA-AR on students' learning outcomes, followed by a qualitative phase to further explore the contextual factors, learning dynamics, and implementation challenges. Each type of data—test, observation, and interview—followed a distinct collection and analysis procedure, as described in the following sections.

a) Test to Produce Scores

In the quantitative phase, pre- and post-tests were administered to 48 eighth-grade students. The test instruments consisted of five open-ended questions designed to measure students' understanding of 3D geometry concepts across three dimensions namely.

1) Representation – the ability to visualize and represent 3D objects,
2) Spatial structure – understanding spatial relationships within geometric figures, and
3) Measurement – the ability to calculate surface area and volume.

These instruments were validated by mathematics education experts to ensure content and construct validity and reliability. The collected test scores were analyzed using a one-sample t-test to determine whether there was a significant improvement in students' comprehension after learning with ITMA-AR.

b) Observation

To complement the test data, structured classroom observations were conducted to understand how ITMA-AR was implemented in real classroom settings. Observations focused on the integration of AR technology, the nature of teacher-student and peer interactions, students' engagement indicators (e.g., enthusiasm, collaboration), and any technical or pedagogical challenges encountered during instruction. These observations were carried out across five learning sessions using a non-participatory method. Field observations were systematically recorded using a predefined guide. The data obtained from observation were categorized and analyzed qualitatively using GT coding to triangulate with the interview results.

c) Interview, Record, and Transcript

The qualitative phase also included semi-structured interviews to gain deeper insight into the experiences of teachers and students in using ITMA-AR. A subset of participants was purposively selected for this phase namely two mathematics teachers and three students selected based on the level of engagement and test performance during the intervention.

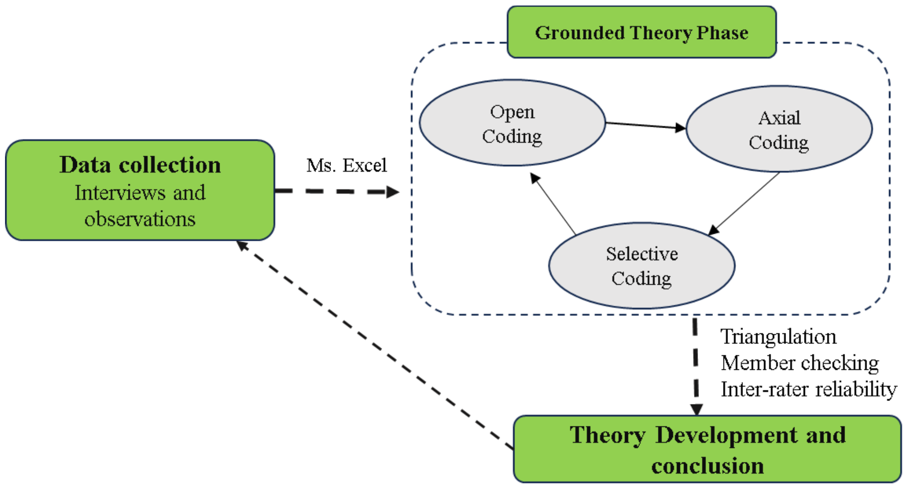
All interviews were audio recorded, transcribed verbatim, and analyzed using a GT method which included the following steps.

- Open Coding: Transcripts were reviewed, and meaningful segments were labeled with initial codes (e.g., “student motivation,” “ease of use,” “technical issues”).
- Axial Coding: These initial codes were grouped into broader categories (e.g., “Motivation,” “Engagement,” “Technical Obstacles”), and interrelationships among categories were identified.
- Selective Coding: Core categories were synthesized into a conceptual model to explain how ITMA-AR influenced classroom learning and what obstacles affected its effectiveness.

The coding process was carried out using Microsoft Excel, and all results were validated through peer review to ensure trustworthiness. The final GT presented a contextualized understanding of the use of ITMA-AR in the mathematics classroom, as showed in Figures 2 and 3.

Figure 2.

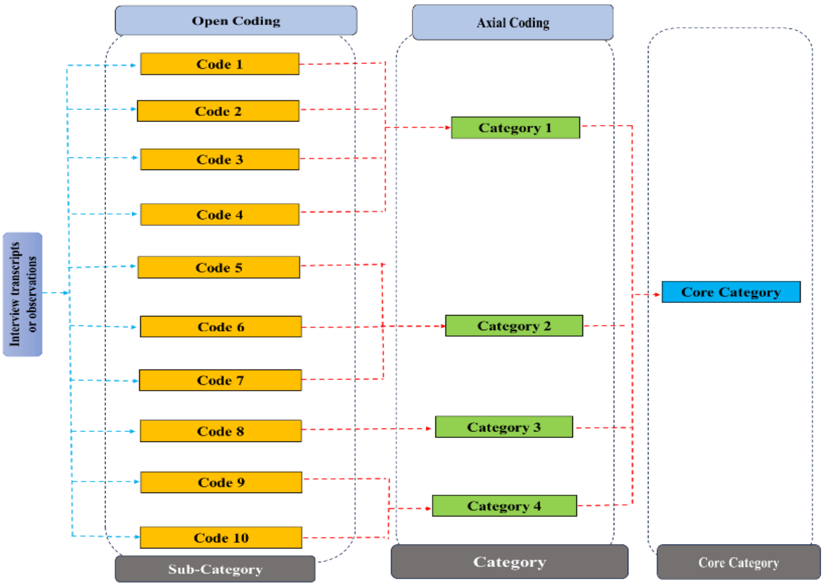
Detailed Scheme of Data Analysis Workflow



To ensure the validity of the results, this study adopted the method of triangulation by combining interviews, observations, and tests. It also used source triangulation by including both teachers and students. Method triangulation allowed for the integration of different types of data—verbal (interview transcripts), behavioral (observation notes), and performance-based (test results)—to cross-check the consistency of results. Meanwhile, source triangulation provided diverse perspectives from educators and learners, which increased the credibility and depth of the results. By gathering insights from these multiple viewpoints, the authors were able to cross-verify the information, ensuring that the results were not biased or limited to one side. This multi-faceted and holistic method offered a more accurate and nuanced understanding of how AR enhanced students' comprehension of 3D geometry concepts.

Figure 3.

Example of GT Output with Categorizing of Codes



Ethical Consideration

This study was conducted in full adherence to ethical analysis standards to ensure the protection of participants' rights, privacy, and well-being. The participants consisted of two mathematics teachers and 48 eighth-grade students from two classes namely VIII-B and VIII-E at a public junior high school in Indramayu Regency, West Java, Indonesia. Before the implementation of the learning activities, all students received a clear explanation regarding the study's purpose, the use of the ITMA-AR application, and the rights as participants. Informed consent was obtained from all 48 students, who voluntarily agreed to participate. Additionally, students were given a technical orientation to help the students understand how to use the AR application and engage effectively in the learning process.

Students' identities were kept confidential, and all data such as observations, interview transcripts, documentation, worksheets, and results from pre- and post-tests were stored securely and reported anonymously. The two teachers, a 38-year-old male and a 34-year-old female with experience in teaching geometry, voluntarily participated and served as key informants through interviews and classroom observations. Students were selected based on the readiness for AR-based learning, the relevance of the learning materials, and the availability of required devices and supporting facilities. Consistent with qualitative analysis practices, the authors also acted as a key instrument playing a central role in data collection, interpretation, and validation while also using supporting instruments such as observation guides, interview protocols, and comprehension tests. All study procedures were carried out ethically, and participants were informed of the right to withdraw at any time without any consequences.

RESULTS AND DISCUSSION

Results

Enhancing Geometry Understanding

Test data from 23 students in class VIII-B and 25 in class VIII-E showed a significant increase in geometry understanding after the implementation of ITMA-AR. Before conducting inferential analysis, a normality test was performed using the Kolmogorov-Smirnov method to ensure that the data distribution met the assumptions for parametric testing. The results showed that the data from both classes were normally distributed ($p > 0.05$), thereby allowing for further analysis using parametric methods. Descriptively, before the intervention, the average pre-test score in class VIII-B was 56.91 which increased significantly to 72.09 in the post-test. Similarly, in class VIII-E, the average pre-test score was 65.25 and rose to 78.92 after the ITMA-AR intervention. These results showed a consistent improvement in students' understanding of 3D geometry concepts across both classes. To confirm these results, a paired-sample t-test was conducted showing that the differences between the pre- and post-test scores in both classes were statistically significant ($p < 0.05$). This suggested that the use of ITMA-AR had a positive impact on enhancing students' comprehension of geometric concepts. More detailed statistical results are presented in Table 2.

Table 2.

3D Geometry Comprehension Test Results

Class	Score test	N	Descriptive Statistics		Paired t-test		
			Mean	SD	t	df	Sig. (2-tailed
Class VIII-B	Pre-test	23	56.91	8.597	-6.311	22	.000
	Post-test	23	72.09	9.639			
Class VIII-E	Pre-test	25	65.28	8.711	-6.565	24	.000
	Post-test	25	78.92	8.236			

Based on the inferential analysis of class VIII-B and VIII-E data, there was a significant increase in students' geometry understanding after the learning intervention. In class VIII-B, the average pre-test score of 56.91 increased to 72.09 in the post-test with a t-test result of -6.311 and a significance value of 0.000 showing a statistically significant difference. A similar trend was observed in class VIII-E, where the average pre-test score of 65.28 increased to 78.92 in the post-test with a t-value of -6.565 and a significance of 0.000. The very low significance values in both classes ($p < 0.05$) confirmed that the increase in students' understanding of geometry after the implementation of ITMA-AR was statistically significant. These results showed that the intervention was effective in improving students' learning outcomes in 3D geometry. The use of ITMA-AR showed great potential for enhancing students' conceptual understanding and is feasible for integration into classroom instruction. Furthermore, an analysis of the proportion of correct answers among all 48 students from both classes showed an increase in correct responses for each question item. The results are presented in Table 3.

Table 3.

The proportion of Correct Answers in Pre-test and Post-test Students in Classes VIII-B and VIII-E

Indicator	Proportion of Correct Answers Pre-test		Proportion of Correct Answers Post-test	
	N	%	N	%
1. Define 3D geometric elements.	26	4.17	40	83.33
2. Drawing 3D geometric nets.	19	39.58	33	68.75
3. Determining the combined surface area of 3D geometry.	16	33.33	26	54.17
4. Determining 3D geometry volume.	21	43.75	30	65.21
5. Average		42.71		67.86

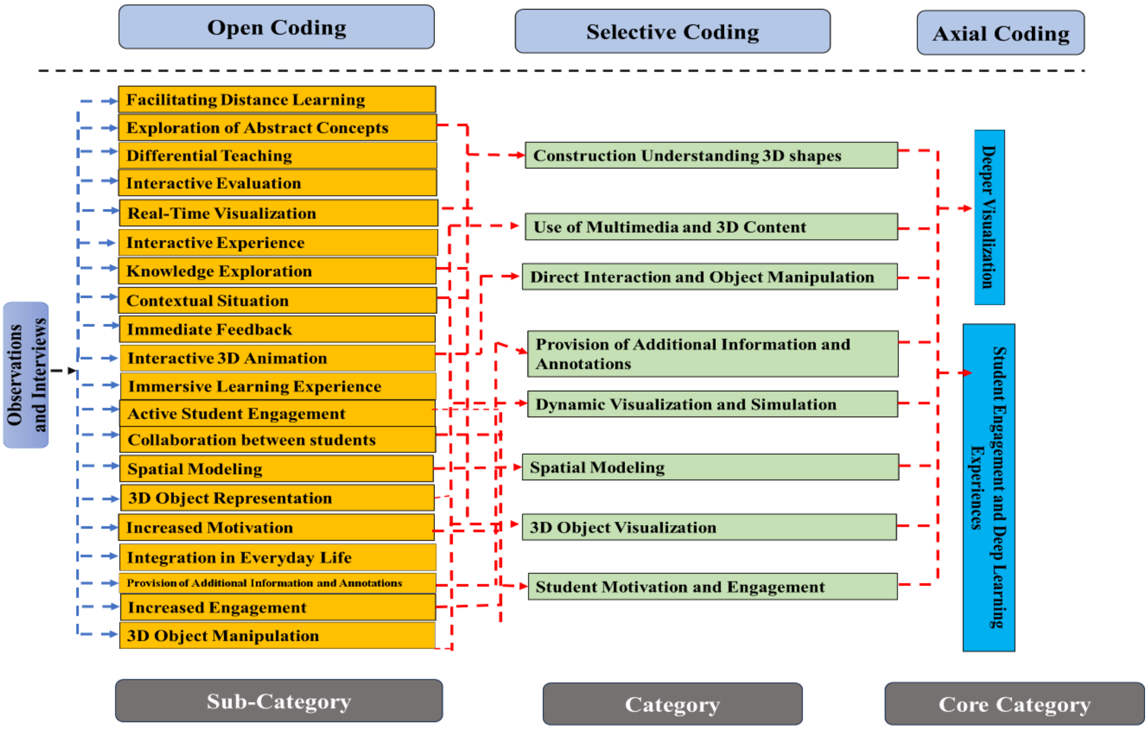
Based on Table 3, students’ understanding of 3D geometry improved significantly after using ITMA-AR. The proportion of correct answers increased across all four indicators namely identifying 3D elements (from 54.17% to 83.33%), drawing nets of 3D shapes (39.58% to 68.75%), calculating surface area (33.33% to 54.17%), and determining volume (43.75% to 65.21%). The overall average score also rose from 42.71% to 67.86%, reflecting an increase of 25.15% points. These results showed that the ITMA-AR intervention effectively enhanced students’ conceptual understanding and problem-solving skills in 3D geometry, particularly among students in classes VIII-B and VIII-E.

Potentials of AR Usage Based on Interviews and Observation

Based on the GT analysis of interview data from both teachers and students, the use of ITMA-AR showed strong potential for enhancing 3D geometry learning. Although test scores provided insight into students’ cognitive achievement, the students did not fully capture the underlying experiences, perceptions, or classroom dynamics associated with AR integration. Therefore, interviews were conducted to explore these qualitative aspects in depth. The results of the GT coding process as indicated in Figure 4 showed key themes such as increased student engagement, improved visualization of 3D concepts, and enhanced motivation. The results outlined the value of incorporating AR into geometry instruction and offered a more nuanced understanding of its educational benefits beyond what quantitative measures could predict.

Figure 4.

The Potentials of AR Based on Its Characteristics



(a) Deep Visualization

AR technology provided immersive visualization capabilities that greatly enhanced students' understanding of 3D geometry concepts. In 3D geometry learning, immersive visualization was essential for understanding the shape, structure, and properties of complex spatial objects. AR technology allowed students to view geometric objects in realistic three-dimensional forms as though physically present. Through AR applications, students were able to rotate, zoom, and manipulate 3D objects which enabled the students to examine every angle and aspect—something difficult to achieve with two-dimensional images. For example, students could observe how the base and lateral faces interact, helping them understand the structure of a triangular prism by using AR. The students explored the planes, angles, and surface interactions which provided clearer and more detailed insights into the structure of 3D geometric objects.

The results on AR's visualization potential were confirmed through triangulation of sources—teachers and students—who agreed that AR's characteristics significantly helped students grasp complex spatial properties through immersive visualization. Excerpt from an interview between the author (R) and the teacher (T):

R: Can you explain how AR is used in your class?

Q: Of course. We started using AR technology in 3D geometry class. We use AR applications integrated with textbooks. Students seem to follow the learning well.

R: Do you see the use of AR can help students visualize 3D geometric objects?

Q: Absolutely. Based on observations, students are seen using their smartphones to view and manipulate 3D geometric objects that appear on tablets or smartphones. Students also appear to note important information and knowledge from shapes such as cubes, blocks, and triangular prisms.

The interview confirmed that in-depth visualization had a strong potential to support students' understanding of 3D geometry. Moreover, student interviews showed that AR significantly aided the direct visualization of geometric objects. This was confirmed through interviews between the author (R) and students (S):

R: Do you enjoy learning using AR?

S: Of course, sir.

R: What aspects do you enjoy learning using AR?

S: When viewing 3D geometric object animations on a mobile phone that can be viewed from various sides, and can be enlarged, see the space in the 3D geometric object, sir.

The response confirmed that direct interaction with 3D objects through AR not only made learning more engaging but also helped students develop a deeper understanding of geometric concepts.

(b) Student Engagement

Based on GT analysis, part of the main benefits of AR was the ability to make learning more interactive and interesting. When students actively manipulated objects and explored concepts through AR, students' motivation to learn increased significantly. Students who were usually less interested in mathematics showed increased interest and participation when AR technology was included. Students enjoyed direct interaction with 3D geometric object animations. The interesting features of AR were conveyed in the following excerpt from the author's interview (R) with the Teacher (T):

R: In addition to what has been explained previously, does the use of AR make students actively engaged in the 3D geometry learning process?

T: Based on direct observation, it seems that students interact directly with 3D objects, and students become more active in learning 3D geometry. Students do not only sit and listen to the teacher's explanation but also participate in exploring and manipulating geometric objects.

R: At what stage are students more active in learning with AR?

T: At the exploration and evaluation stages. This is because... R: At what stage are students more active in learning with AR?

T: At the exploration and evaluation stages. This is because, in the exploration stage, students are allowed to interact directly with 3D models through AR technology, so that they can understand the concept more deeply through visual and manipulative experiences. Meanwhile, in the evaluation stage, students are more active because students can retransmit the understanding that students have obtained by completing AR-based questions or tasks that test geometry concepts learned.

The interview excerpts showed that students felt more engaged and motivated when using AR in learning. This confirmed that the use of AR not only increased interactivity but also made the learning process more interesting and enjoyable for students.

c) Profound Learning Experience

Based on the GT analysis, AR technology significantly enhanced the overall learning experience in 3D geometry by providing a richer and deeper understanding through its interactive features. Unlike traditional methods that relied on textbooks and whiteboards, AR brought geometry concepts to life in realistic and relevant contexts. This immersive method enabled students to visualize and interact with 3D objects, making abstract ideas more tangible and easier to understand. The profound impact of AR on the learning experience was evident from the following excerpt from the author's interview with the teacher:

R: How does AR affect students' overall learning experience?

T: AR greatly affects students' learning experiences by making them more profound and comprehensive. Students do not just look at images in textbooks or on the whiteboard; they can interact directly with geometric objects. This makes learning more concrete and holistic. Students can experience and understand concepts more realistically and practically.

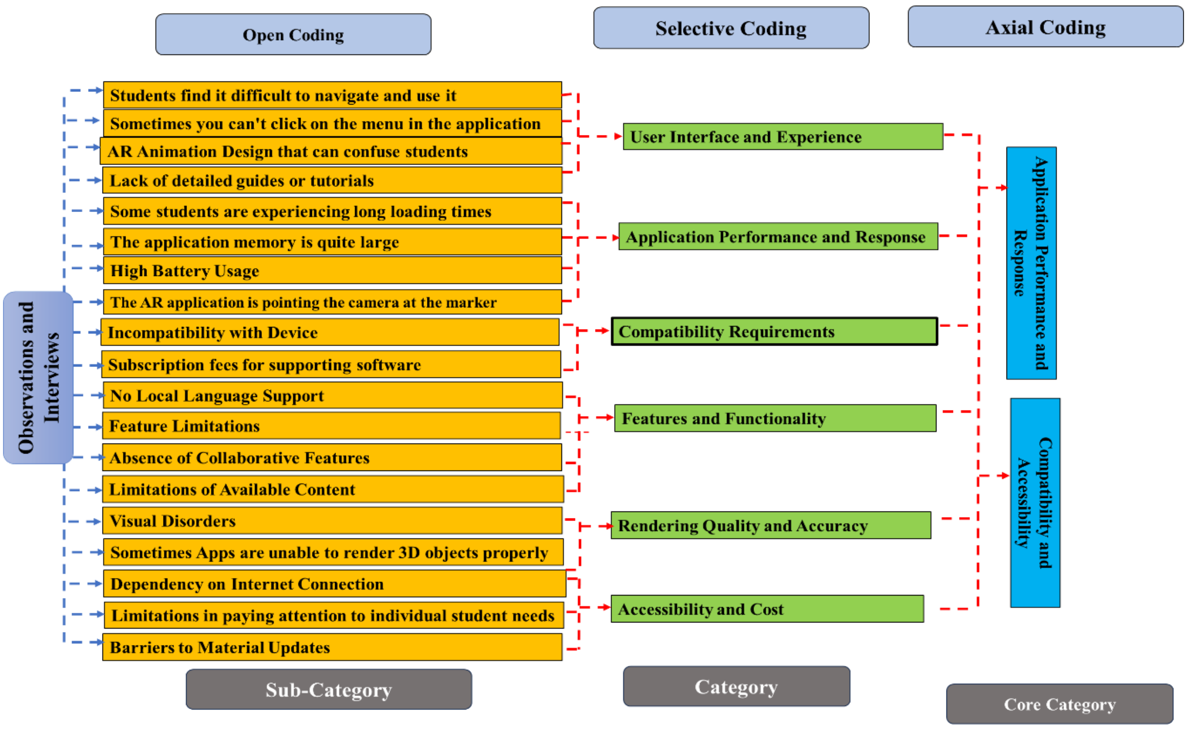
By allowing students to manipulate and explore 3D objects, AR transformed learning into an engaging and interactive process. This hands-on method fostered a deeper understanding and better retention of geometric concepts, making the learning experience more meaningful and impactful.

Obstacles to Learning with AR

1. Internal Obstacles

Figure 5.

Results of GT Analysis Related to Internal AR Obstacles



Although AR technology had great potential to improve students' understanding of 3D geometry, its implementation faced several obstacles based on the GT analysis. The study identified two obstacles namely internal and external obstacles. Internal obstacles originated from the characteristics of the AR application or the processes engaged in its usage. As shown in Figure 5, the internal obstacles that evolved from the GT analysis included application performance and responsiveness, as well as compatibility and accessibility issues.

(a) Application Performance and Responsiveness

According to GT analysis, part of the main internal obstacles was the performance and responsiveness of AR applications. This included various issues such as delayed responses, instability that caused disruptions or crashes, and unsatisfactory visual quality. When the AR application did not function smoothly, students experienced difficulties in understanding and interacting with the 3D geometry content. Obstacles related to application performance and responsiveness were showed in the following interview excerpt between the author and the teacher.

R: Can you explain more about obstacles caused by the AR application?

S: One of the main obstacles is application performance. Sometimes the AR application feels slow and unresponsive, specifically if many students use the same application at the same time. This makes the learning experience less effective because we have to wait a long time or repeat the process. In addition, sometimes, the application suddenly crashes or does not respond.

R: If faced with such obstacles, what solution do you do?

T: Usually I ask to close the application, then restart it.

The use of AR applications in learning, while offering many benefits also posed technical obstacles that interfered with the effectiveness of the teaching and learning process. Problems such as lagging or crashing applications showed that technology did not operate smoothly, specifically when used by many students at once. The solution provided namely closing and reopening the application represented a temporary fix rather than a fundamental resolution to the problem.

(b) Compatibility and Accessibility

Another significant internal obstacle was compatibility and accessibility. This referred to the availability of devices that supported AR applications such as smartphones or tablets with required sensors and access to stable, high-speed internet connections (Figure 5). Students who lacked access to suitable devices or reliable internet struggled to use AR effectively in learning 3D geometry. In interviews, students expressed frustrations with these issues.

R: Can you explain further about these barriers?

S: One of the main barriers is compatibility issues. Not all devices we have at school or home support AR applications well. Some AR applications require devices with high specifications or special features like specific cameras, so not all students can use them smoothly. This makes some of us lag because we cannot access the same applications.

R: How does this compatibility issue affect your learning experience?

S: This compatibility issue is quite annoying. When AR applications cannot run on my device, I have to look for alternative solutions or borrow devices from friends, which are not always available. This hampers my learning process because I cannot directly follow the instructions from the researchers or explore the material freely.

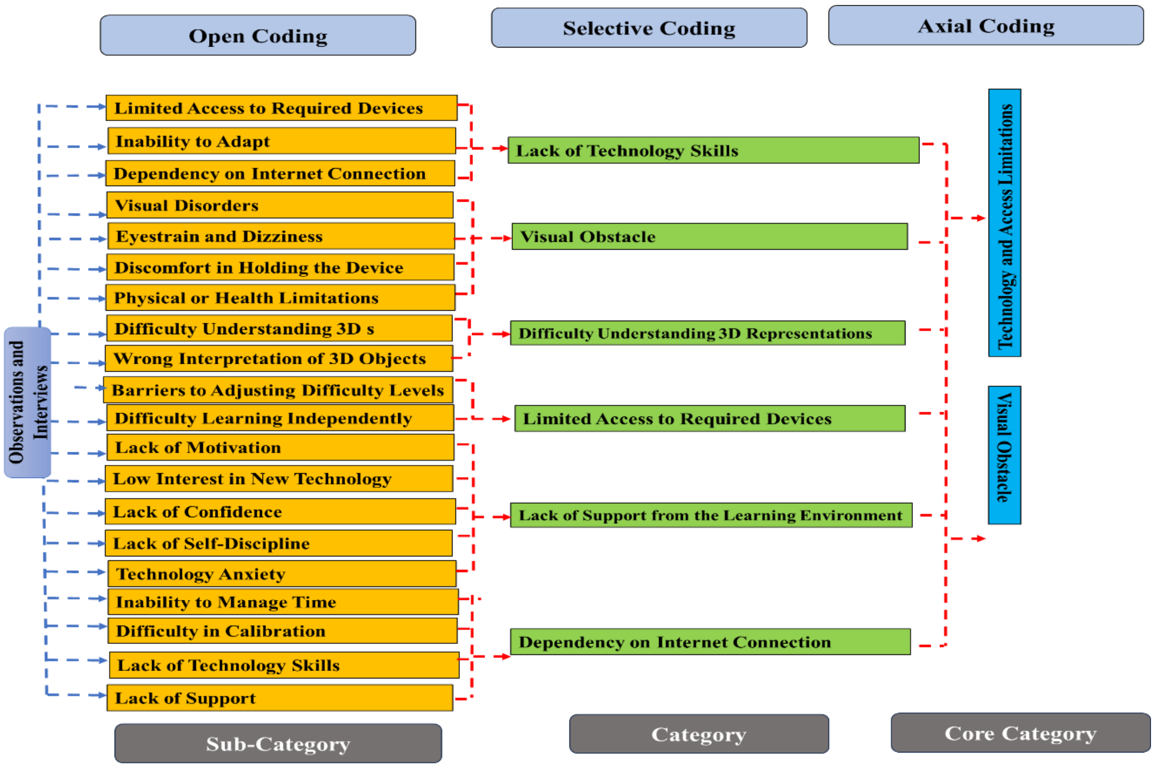
The compatibility and accessibility issues created significant inequalities in students' learning experiences, preventing some from fully benefiting from AR technology. In summary, while AR held promise for transforming 3D geometry learning, addressing the internal barriers was essential for its effective use. Ensuring that AR apps were responsive, widely compatible, and accessible to all students was crucial to maximizing educational impact.

2. External Obstacles

In addition to internal challenges, GT analysis showed that AR technology encountered external obstacles. These barriers originated from factors beyond the control of users or systems, which limited or disrupted the effective use of AR in education. According to Figure 6, external barriers included limitations in technology and access, as well as visualization-related and physical constraints affecting students.

Figure 6.

Results of GT Analysis Related to Obstacles Due to External Factors



(a) Technology and Access Limitations

Based on GT analysis, part of the external obstacles that evolved through selective coding was limited technology and access. Implementing AR technology required sophisticated hardware and software. Observations during learning also showed that many students lacked access to necessary devices, such as smartphones, tablets, or computers with adequate specifications. In addition, a stable and fast internet connection was important to access AR applications and the required 3D geometry content. The results were reinforced by the following interview excerpt between the author and the teacher.

R: Explain further, what are the external obstacles to using AR applications in 3D Geometry learning.

Q: The most common obstacle is that not all students have a cell phone to use in learning. In addition, some students have cell phones but do not support when installing the AR application. Some students do not have enough internet quota to use the AR application.

R: Are there any other obstacles?

Q: Internet connection is also another obstacle.

The technological obstacles confirmed that students without access to the necessary devices or the internet could not fully engage with AR learning. Moreover, disparities in technology access across regions widened the digital divide. Support from educational institutions was essential to ensure the equitable and effective implementation of AR in diverse learning environments.

(b) Visual Obstacles

Another external obstacle identified in the GT analysis was visualization fatigue. This referred to the strain students experienced when engaging with 3D animations on-screen for extended periods. The visual strain could reduce students' engagement and impair the ability to retain or explore geometric content effectively. The following interview excerpt showed this issue.

R: In addition to barriers related to technology access, what other barriers arise while using AR?

Q: Based on observations, most students complained about the visualization process of 3D geometric animations that appeared on their cell phones. Students admitted to having a little headache because they watched AR animations for too long.

R: What efforts did you make to overcome this?

Q: Usually I direct students to take notes first and discuss the results of exploration with AR with their friends.

This interview outlined that prolonged use of touchscreen devices for AR could hinder learning. Visual fatigue along with unresponsive or hard-to-operate apps, limited the depth of spatial understanding students could achieve. Additionally, limited screen interaction reduced the immersive potential of AR compared to real-world manipulation, thus diminishing the overall learning experience.

DISCUSSION

This study shows that the use of AR in learning 3D Geometry offers several potentials categorized into internal and external. Internal potentials arise from the intrinsic characteristics of AR technology such as the ability to provide deep visualization, enhance student engagement, and create a more immersive learning experience. On the other hand, external potentials comprise the broader impacts on learning outcomes including improved understanding of concepts and 3D visualization, as well as increased student motivation and interest in the learning process.

Part of the most significant intrinsic characteristics of AR is its ability to provide deep visualization. According to Cetintav and Yilmaz (2023), AR allows students to interact directly with 3D models, making it easier to understand complex geometric concepts. AR shows geometric objects in three-dimensional forms that can be rotated and enlarged, giving students a more comprehensive and intuitive view of the shape and structure of the objects. This study correlates with the results of Hwang et al. (2023) showing that interactive visualization provided by AR helps students understand abstract concepts more effectively. Through AR, concepts that are difficult to visualize with conventional methods become easier to understand because students can observe real representations of those concepts.

Additionally, AR technology proves effective in increasing student engagement in the learning process. A study by Chang et al. (2022) showed that the use of AR made students more active and engaged in class, reducing the boredom often arose with conventional teaching methods. AR provides a more interactive learning experience, where students are not passive recipients of information but also active participants in the learning process. This result was supported by Lin et al. (2015) who found that AR could enhance active student participation, making learning more interesting and interactive. Students are more motivated to explore the lesson material because the students can see and manipulate objects relevant to the subject matter with AR. Furthermore, Wu et al. (2022) found that AR created a more immersive learning experience by combining kinesthetic and visual learning. This provides a richer and deeper learning environment, helping students to understand content more holistically. Kinesthetic learning which includes physical activity and hands-on manipulation of AR objects, enables students to learn through movement and interaction as well as observation and listening. AR supports multiple learning methods such as visualization, direct interaction, and simulation all of which contribute to more effective and meaningful learning.

In terms of enhancing conceptual understanding and 3D visualization, the results are consistent with those of Martín-Gutiérrez et al. (2015) who report that students using AR exhibit a better understanding of geometric concepts compared to those using traditional methods. This improvement occurs because AR provides visual representations of the concepts as shown by Marques et al. (2021). Through AR, students can see how geometric concepts apply in real-world contexts, helping them bridge the gap between theory and practice. Carrera and Asensio (2017) found that AR significantly helped students develop spatial visualization skills. This correlated with the results of Yaniawati et al. (2023) showing that AR-enabled students to view and manipulate 3D objects from various angles, enhancing the understanding of geometric structures. Students can rotate, zoom in, and examine different perspectives of objects, which helps comprehend spatial relationships and the connections between components.

Besides cognitive development, AR also supports students' motivation and interest in learning. This is consistent with Bhagat et al. (2021), who show that AR can increase students' motivation and interest in learning 3D Geometry. Pocan et al. (2023) also showed that AR increased student motivation by making the learning experience more interactive. Students become more enthusiastic due to being engaged actively with the material, observing the immediate results of actions, and enjoying a more hands-on learning experience. Moreover, AR usage leads to improved learning outcomes compared to conventional methods. Alqahtani and Al-Najdi (2023) showed that students using AR exhibited better learning outcomes and deeper understanding. Yip et al. (2023) also supported the result showing that AR enhanced overall learning quality. Students can also learn in a more interactive and immersive manner, which helps to understand the lesson material better and retain the knowledge for a longer period.

In a broader context, the use of AR in learning 3D geometry correlates with constructivist theory which emphasizes the importance of active learning and direct experience in understanding complex concepts. This theory developed by experts such as Vygotsky (1978) and Piaget (1964) emphasized that learning including active student participation and direct interaction with learning materials could enhance understanding and retention (Tudge & Rogoff, 2015). According to constructivist theory, students learn by constructing knowledge through direct experiences and interactions with the environment. Students can further engage actively in the learning process, explore geometric concepts through direct interaction with 3D objects, and build the understanding through these experiences with AR.

Consequently, this study identifies several obstacles to the use of AR in learning 3D Geometry which can be categorized into internal and external obstacles. Internal obstacles relate to the characteristics of AR technology including application performance and responsiveness issues during use, as well as compatibility and accessibility problems. Meanwhile, external obstacles include limited access to technology and visual and physical barriers. These results correlated with several studies such as Alqahtani and Al-Najdi (2023) showing that AR applications often experience technical issues such as unresponsiveness or lag disrupting the learning process. Another issue is compatibility and accessibility, where not all hardware or software supports AR applications as evidenced by Creed et al. (2024). Furthermore, access to the necessary technology remains uneven. As Alqahtani and Al-Najdi (2023) stated, not all schools were equipped with sufficient resources to provide AR-enabled devices for all students which exacerbated the digital divide between different schools.

Limitations of the Study

Although this study showed the promising potential of ITMA-AR in enhancing students' understanding of 3D geometry, it was not without limitations. The analysis was conducted in a limited setting including only two eighth-grade classes in a single junior high school which restricted the generalizability of the results to broader educational contexts. Technological obstacles also posed limitations including internal issues such as slow response and instability of the AR application, as well as external factors comprising of limited access to compatible devices and unstable internet connections. Additionally, the study was conducted over a relatively short period and did not assess the long-term effects of AR-based learning on students' retention and motivation. Qualitative data were also collected from a small group of participants which could not fully represent the diverse experiences of all learners. These limitations suggested the need for further publications including larger and more varied populations, longer implementation periods, and improved technological support to maximize the effectiveness and accessibility of AR in geometry learning.

CONCLUSION

In conclusion, this study found that the personalization of ITMA-AR had significant potential to improve students' understanding of 3D geometry. Based on the GT analysis, potential for personalization of ITMA-AR lay in the characteristics of AR technology which provided deep visualization and increased student engagement. Through the stages of exploration and direct interaction with 3D objects in a virtual environment, AR created a more engaging and immersive learning experience. The implications of AR's characteristics and the use of ITMA-AR helped students enhance the understanding of 3D geometry including identifying the elements that form three-dimensional shapes, drawing 3D nets, determining surface area, and calculating the volume of 3D objects.

Furthermore, this study identified two main obstacles in the implementation of ITMA-AR in 3D geometry learning namely internal and external. Internal obstacles included performance issues with AR applications such as slow response times and instability, as well as compatibility and accessibility problems. External obstacles included limited student access to AR technology and difficulties in visualizing and interacting with virtual objects.

This study recommended giving priority to improving the performance of AR applications—specifically by enhancing the responsiveness and stability—to ensure a smooth user experience and support the effective integration of AR technology into geometry learning. Additionally, expanding device compatibility was essential to allow AR applications to function across a variety of devices, including those with lower specifications. It was also suggested that schools invest in stable, high-speed internet connections. Providing offline capabilities for AR applications could further help mitigate connectivity issues.

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