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Development of mobile augmented reality-based geometry learning games to facilitate spatial reasoning

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Abstract

Geometry learning requires a comprehensive understanding of spatial reasoning, but students face difficulty in mastering the skill. As a virtual technology, Augmented Reality (AR) offers a solution to overcome the challenges in spatial reasoning with the potential to represent and manipulate objects and develop spatial images mentally. Therefore, this research aimed to develop a mobile educational game named GEMBI AR to support students' spatial reasoning skills in geometry learning. The ADDIE model consists of analysis, design, development, implementation, and evaluation phases used to conduct research and development (R&D). The participants included six expert validators, two mathematics teachers, and eighteen eighth graders. In addition, the expert validators validated GEMBI AR in terms of quality. The result showed that GEMBI AR was valid as a geometry learning tool. According to the feedback of teachers and students, GEMBI AR was practical for educational purposes since the application positively impacted spatial reasoning. Students' spatial reasoning skills were also enhanced to compare the differences in the pre-test and post-test using Wilcoxon ($Z = -3.578$, $p = 0.000 < 0.05$). Meanwhile, the N-Gain score of 0.576, showing moderate improvement, reflected gains in spatial perception, mental rotation, and visualization. These findings suggest that GEMBI AR is a functional and valid educational resource useful for helping students develop geometric spatial reasoning. Thus, geometry learning supported by GEMBI AR has the potential to enhance spatial reasoning in secondary school.

Keywords:
Development research, Game-based learning media, Geometry, Mobile augmented reality, Spatial reasoning

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1. INTRODUCTION

Spatial reasoning was reported to play a crucial role in mathematics activities and contributes directly to the achievement of student learning outcomes in geometry (Atit et al., 2022; Atit et al., 2020; Harris et al., 2023; Lombardi et al., 2019). This spatial reasoning skill includes recognizing and using spatial patterns on a large and small scale (Woolcott et al., 2022). In geometry learning, spatial reasoning plays an important role in solving problems, identifying patterns, and understanding geometric properties (Anwar et al., 2023; Buckley et al., 2019). Therefore, weak spatial reasoning can be a contributing factor to the challenges of student in understanding geometry, affecting mathematics learning outcomes (Hawes et al., 2022). Currently, development is stated as a goal of mathematics education from kindergarten to university (Cheng & Mix, 2014; Rich & Brendefur, 2018). In this context, spatial reasoning is essential to intellectual skill and successful academic performance (Maeda & Yoon, 2013). Moreover, schools are the right and strategic place to develop skill because the process can be integrated into every learning activity (Sa'dijah et al., 2021).

Students with good spatial reasoning characteristics can understand the relationship between shapes, objects, and space (Supli & Yan, 2024). However, Ismail et al. (2020) reported that students experience difficulty in constructing geometric spatial structures to solve problems related to the visualization process. Since visualization is an element of spatial reasoning skill (Ramful et al., 2017), facilitating development is important. Previous research stated that three main components of spatial reasoning skill were crucial for the success of student in geometry learning (Otálora & Taborda-Osorio, 2025; Ramful et al., 2017; Supli & Yan, 2024; Wulandari et al., 2019). These components include mental rotation, spatial perception, and spatial visualization. Mental rotation is the ability to solve problems related to changes in the rotation of an object. Meanwhile, spatial perception is the act of solving problems from an object through different perspectives. Spatial visualization is the ability to solve problems related to imagining or describing changes in the shape or position of an object. Some literature reported that this ability could be enhanced through certain learning arrangements, such as adding elements to visualize and manipulate objects (Lowrie et al., 2021; Septia et al., 2018; Woolcott et al., 2022). Several research have reported the positive effects of virtual technology settings on learning spatial reasoning (Anggraini et al., 2020; Carrera & Asensio, 2017; Di & Zheng, 2022; MacDowell & Lock, 2022; Woolcott et al., 2022). Virtual technology in the form of AR can help students present objects mentally, as well as develop and manipulate the ability to build spatial images (Ahmad & Junaini, 2020; Lee, 2012). Therefore, AR has become a promising research focus to support spatial reasoning skill of students.

The use of AR technology in classroom learning is carried out with the help of mobile devices such as smartphones or tablets (Alkhattabi, 2017). Mobile Augmented Reality (MAR) is a technology that allows reality experiences to be carried out through smartphones or tablets (Papakostas et al., 2023). These can be realized by using cameras and sensors on the mobile device (Costa et al., 2020). Therefore, students use the mobile device to view additional objects or information that cannot be seen in the real world. On the other hand, its flexibility, which can be installed on a smartphone or tablet, makes it easier to carry and use anywhere (Mandala & Setyaningrum, 2024).

MAR-based learning media help students understand mathematics learning geometry (Gargrish et al., 2020; İbili et al., 2020; Putri et al., 2023; Su et al., 2022). The concept enables the imagination and visualization of spatial aspect to make the right decisions in overcoming space-related problems. Furthermore, realistic visualization is one of the factors influencing geometry learning that can be supported by technology, to increase engagement and understanding as a form of immersive experience (Su et al., 2022). The use of virtual technology such as MAR opens up an innovation known as immersive learning (Bizami et al., 2023; Mystakidis & Lympouridis, 2023). Based on constructivism, immersive learning allows students to build knowledge and understanding through interaction with virtual environments to provide meaningful experiences (Dengel, 2022; Songkram et al., 2021). The benefits of constructivist-based concepts, such as active, situational, or experimental learning in promoting spatial reasoning are achieved by constructing with 3D objects (Do & Lee, 2009), exploring model designs of object interaction and control (Krüger et al., 2022) or manipulation using rotation-based mechanisms (Cao et al., 2023; Papakostas et al., 2021).

Technological tools supporting immersive learning experiences have become a significant concern in the education sector, considering the potential and benefits (Mohsen & Alangari, 2024). The integration of AR into learning media can bridge between concrete and digital media (Baxter & Hainey, 2024). According to previous research, media development was used as an alternative solution to improve classroom teaching quality (Murtafiah et al., 2019). Several AR applications have been developed for geometry learning, showing a positive impact in improving visual perception through 3D visualization and other geometric representations to support spatial skill (Gargrish et al., 2022; İbili et al., 2020; Krüger et al., 2022; Nadzeri et al., 2023; Putri et al., 2023; Richardo et al., 2023). Previous research have only focused on the use of AR for spatial visualization skill. However, the ability to perform mental rotation and spatial perception has become a major challenge in mathematics education. Geo-Math application developed by Ikhsan et al. (2024) used GeoGebra AR to visualize 3D geometries and manipulate objects such as rotation, scaling, and transformation. In this context, application-integrated Geogebra AR could contribute to visualization and mental rotation skill. The application did not provide any physical interaction or direct connectivity between the physical and digital environments in learning process. Advanced prior knowledge of mathematical equations is required to generate objects in AR. This is challenging for some individuals because the process needs a trial-and-error process.

The use of AR in education settings was recommended because the application showed enhancement of experience, supported the achievement of learning outcomes in geometry, and strengthened visual ability (Ikhsan et al., 2024; Nindiasari et al., 2024; Singh et al., 2024). Previous research have examined the technology as a tool to enhance the visual ability of students (Ikhsan et al., 2024; Papakostas et al., 2021). However, research concerning the impact of AR on specific components of spatial reasoning remains limited. The integration of AR into geometry learning and the effectiveness of AR-based activities to support the three main components of spatial reasoning are important. Therefore, this research aims to develop learning media in AR-based mobile geometry educational game to support spatial reasoning. MAR-based learning media was developed to support students in obtaining immersive learning experiences. Moreover, the media is developed by adjusting content in appliacable curriculum and geometry content in secondary school. Therefore, the developed media can motivate learning and make it easier to understand the material according to the competencies to be achieved. Learning media in this research is used to support spatial reasoning skill of students. Aspects of spatial reasoning refer to three leading indicators, namely spatial perception, mental rotation, and spatial visualization. In addition, development of learning tool contributes to immersive mathematics learning tools and assists teachers in teaching geometry topics.

2. METHOD

2.1. Research Design and Procedures

This research conducted Research and Development (R&D) with the ADDIE model, which has five phases including analysis, design, development, implementation, and evaluation (Branch, 2009). The model was selected because the phases were straightforward and had a systematic manner following this research objective (Al-Amri et al., 2023). Figure 1 shows development of the ADDIE model phases (Sutarni et al., 2024).

Figure 1. Phases of the ADDIE model

The procedures and development steps follow the ADDIE model phases described as follows.

Phase 1: (A) Analysis of Needs

The analysis phase assessed needs, identified problems, and analyzed development needs. At this phase, a needs analysis is carried out to evaluate requirements and identify problems in geometry learning related to spatial reasoning skill. This initial phase was carried out by a literature review to identify previous theories and results. Subsequently, observation and interviews were conducted with several mathematics teachers. The interviews focused on the availability of learning media and the implementation in the school, as well as the challenges faced by teachers. The needs of teachers and preferences of students for the use of AR technology were considered for development. Meanwhile, the availability of infrastructure, such as devices supporting AR was also analyzed to ensure readiness to use media. A content analysis was carried out to identify geometry concepts considered difficult, specifically those requiring spatial reasoning skill. The identified concept was the main content in AR-based learning media named GEMBI AR.

Phase 2: (D) Design

The activity at this phase is to design a product concept in the form of a MAR-based educational game oriented to spatial reasoning skill and assessment instruments. The features were adjusted to the objectives of immersive learning, scenarios or activities of teaching geometry, as well as learning materials by the applicable curriculum. The essence of the activity is to design the GEMBI AR product concept as a blueprint. In addition, assessment instruments are prepared to assess the quality of media developed based on validity, practicality, and effectiveness, as reviewed from spatial reasoning capabilities.

Phase 3: (D) Development of MAR

At this phase of development, media development is carried out and the activities realize the design of GEMBI AR media products previously designed. Development is divided into the phase of making a printed book as a target image and application. The creation of MAR or printed books is achieved using MS Publisher application. Moreover, the GEMBI AR application was made utilizing the Unity program and converted using the Android Studio application. Learning media development is validated by content (CE) and media experts (ME). The results of validation and inputs are used to assess the validity of the developed media. The three experts had at least 5 years of experience in the respective fields. Validation of spatial reasoning skill test instrument was conducted out by two experts. Furthermore, revisions were made based on input from the experts. The results showed a Cronbach's Alpha value of 0.824 since the test instrument was reliable (Retnawati, 2016).

Phase 4: (I) Implementation

Implementation phase consists of two major activities, namely the pilot research and the field test. The primary purpose was to evaluate the practicality and effectiveness of GEMBI AR to develop spatial reasoning skill of students. Firstly, the trial applied the developed instrument to a class in accordance with the target subject. This assessed the validity and reliability of the instruments to ascertain the effectiveness in measuring spatial reasoning skill. Secondly, GEMBI AR testing was carried out to check when the functions of the application work as intended and examine the perspective of teachers in terms of interface and usability to enhance learning.

The field test is performed to the students as real users of the GEMBI AR in the classroom environment. The procedure starts with a pre-test where the main objective is to measure the initial spatial reasoning skill before using GEMBI AR. In this context, the result is compared with the post-test to evaluate the impact. The integrated learning method using GEMBI AR spans three sessions since students participate in game to understand geometry concepts and enhance spatial reasoning. After learning sessions, a post-test is given to try and measure the strides achieved in terms of swaying spatial reasoning capabilities of the learners. The actions of the teacher and students are considered as well as the activities on observation sheets to assess the use of GEMBI AR in a real classroom. Furthermore, responses to questionnaires are submitted after the implementation media to improve the quality. This feedback establishes a process to improve the practice of the application and recommendations on the processes.

Phase 5: (E) Evaluation

In phase 5, an evaluation was carried out regarding the practicality and effectiveness of GEMBI AR in developing students' spatial reasoning skills. The strategy starts with an analysis of data to provide validation and reliability of test instruments. These instruments receive necessary editing and adjustment to adequately evaluate the level of spatial reasoning in students. Moreover, the feedback of the teachers given during the black box testing was used to assess the usability and functionality of the application. This is important for the identification of present or future problems with the technology and suggestions to incorporate the application into teaching and learning processes.

In the field test, the quantitative analysis concentrates on the testing of the practicality and effectiveness of GEMBI AR in real classroom environments. Practicality was assessed using questionnaires completed by teachers and students with a Likert scale, covering aspects such as interface design, ease of operation, language clarity, relevance to the learning material, and user satisfaction. The results of this questionnaire yield valuable feedback on user acceptance and experience of the media. The questionnaire responses were used as a consideration for revising the developed media, ensuring that the media aligns with expectations and needs in the field.

After this phase, a quantitative analysis is conducted with pre and post-test to determine significant improvement in spatial reasoning skill of students following the use of GEMBI AR. The pre and post intervention results are compared with the aim of determining whether there was any significant enhancement of spatial reasoning skills after among students. Meanwhile, the N-Gain score is used to assess improvement at the overall and individual levels of spatial reasoning namely, spatial perception, mental rotation, and spatial visualization. In this context, the evaluation focuses on the role of GEMBI AR in advancing components of low spatial abilities and emphasizes the need for precise comprehension of the functionalities. The N-Gain analysis further helps in exploring the differential impact of learning media in terms of specific dimensions.

2.2. Participants

This research was validated by a total of six expert validators, including three content experts (CE) and three media experts (ME). A total of four experts are lecturers at a public university, while the remaining two are mathematics teachers in lower secondary schools. The expert validator criteria include a minimum of 5 years of teaching experience, an academic position as a professor or doctor, or mathematics teacher experience according to the field of expertise (see Table 1). CE has expertise in teaching methods, assessments, and mathematics materials related to curriculum development and implementation. ME are experienced in developing AR-based media on mobile. CE evaluated the validity of learning resources in terms of relevance, accuracy, and propriety, while ME assessed the performance, design, and features of GEMBI AR application. In this context, the subject content of learning game and media used were grounded in educational principles and technological soundness.

Table 1. List of expert validators for The GEMBI AR

	Validators	Expert's Positions	Expertise
Content Experts	CE-1	Professor	Teaching methods and assessment in mathematics education
	CE-2	Associate professor	Mathematical reasoning and literacy
	CE-3	Vice principals for curriculum and mathematics teacher	Curriculum development and implementation

	Validators	Expert's Positions	Expertise
Media Experts	ME-1	Professor	Mathematics instructional media
	ME-2	Associate professor	Mathematics instructional media
	ME-3	Mathematics teacher	Mathematics learning

In the Implementation phase, two mathematics teachers took part in a pilot research of the application and provided feedback regarding the instructional aspects. Furthermore, eighteen of the eighth graders participated as users during the field testing. This research was implemented in a private lower secondary school in Jember Regency, East Java, Indonesia. The selection of students was carried out by applying a purposive sampling method. This method was used because the students studied the subject matter of polyhedra to enhance spatial reasoning through AR.

Purposive sampling was used to select the most pertinent sample for the research objectives. The participated students were learning geometry with the topic of polyhedra, had basic geometry in primary school, and were skilled at operating smartphones to take full advantage of learning media. The results are not necessarily directed towards the generalization of the phenomenon. However, the effectiveness and practicality of GEMBI AR are explored in students within the targeted educational setting.

2.3. Data Collection

Data collection was conducted using test and non-test instruments validated by CE-1 and ME-1. The instrument was revised based on input from the validators until it was deemed valid and was used to assess GEMBI AR in terms of validity, practicality, and effectiveness on spatial reasoning skill. The data collection activities were carried out at different phases of the research such as pilot and field testing to provide thorough evaluation.

Indeterminate instruments in the form of a questionnaire were used to evaluate the criterion-based validity and practical usability of the GEMBI AR. Using a modified Likert scale, the structure included a questionnaire with five options ranging from 1 (very poor) to 5 (very good). CE and ME validators, teachers, and students used the scales to assess the functionality of the application in terms of the relevance of the content was relevant, the complex nature, the design, and the general learning goals. The validity assessment focused on the accuracy and relevance of spatial reasoning tasks and the practicality assessment gathered feedback on the ease of implementation and usability of media in real classroom settings. During the field test phase, the practicality of GEMBI AR was evaluated by assessing the responses of teachers and students with the help of observations and questionnaires.

The effectiveness criteria were set based on a test instrument designed to assess spatial reasoning skill before and after the use of GEMBI AR. This evaluation was achieved in terms of the pre-test and post-test design methods within the field test in three classroom sessions. The three important aspects of spatial reasoning, namely spatial perception, mental rotation, and spatial visualization were important to the comprehension and problem-solving of geometrical relations. The test items were taken from Ramful et al. (2017) to the respondents in geometry educational context since the concept fitted into the existing metrics of spatial reasoning. Additionally, the instrument was critically evaluated by three CE for correctness, and necessary changes were made according to the validation comments and suggestions.

2.4. Data Analysis

The data obtained were used to determine the validity, practicality, and effectiveness of using GEMBI AR media. Validator scores, teacher and student media assessment scores, as well as spatial reasoning skill tests, were analyzed descriptively and quantitatively. In the validity analysis, the proof uses Aiken (1985) with the following equation [1]:

$$V = \frac{\sum s}{n(c-1)} \quad [1]$$

V is the rater agreement index on item validity; s is the value assigned by each rater minus the lowest value in the category used ($s = r - I_0$), where r is the criterion value chosen by the rater, and I_0 is the lowest value used in scoring), n is the number of raters, and c is the number of criteria selected by the rater. The V index ranges from 0-1, and when the agreement index is less than 0.4, between 0.4-0.8, and more than 0.8, then validity is reported to be low validity, medium, and high, respectively (Retnawati, 2016).

The practicality assessment scores are analyzed through descriptive statistical analysis by calculating percentages using the following equation formula [2]:

$$P = \frac{TES}{MTS} \times 100\% \quad [2]$$

Where P is the value of practicality, TES is the total empirical score, and MTS is the maximum total score. The determination of practicality adopted a reference from (Wijayanto et al., 2022) using the five scales shown in Table 2.

Table 2. Practicality data conversion guidelines

Score Interval	Percentage (%)	Category
$\bar{x} > 4.25$	$85.01 - 100.00$	Very Practical
$3.50 < \bar{x} \leq 4.25$	$70.01 - 85.00$	Quite Practical
$2.50 < \bar{x} \leq 3.50$	$50.01 - 70.00$	Less Practical
$\bar{x} < 2.50$	$01.00 - 50.00$	Impractical

The effectiveness analysis was calculated using the paired sample t-test of the SPSS version 20 application, and the N-Gain score was tested to determine when spatial reasoning results increased after using GEMBI AR. In testing the paired sample t-test, the first data test was normality. However, the Wilcoxon non-parametric test was used when the data was abnormal. Data were analyzed with the help of the SPSS version 20 application. In testing the N-Gain using the formula equation, the formula adopted from Hanggara et al. (2024) [3] was used.

$$N - Gain = \frac{Posttest\ score - Pretest\ score}{100 - Pretest\ score} \quad [3]$$

The results of the N-Gain score calculation follow the category guidelines from Nindiasari et al. (2024). The score is categorized as low, moderate, and high when N-Gain score ≤ 0.30, between 0.30 to 0.70, and ≥ 0.70, respectively.

3. RESULTS AND DISCUSSION

3.1. Results

3.1.1. Analysis of Needs

Based on field observations and interviews with mathematics teachers (CE-3), geometry material content selected for development of learning media is polyhedra for eighth grade students. This topic is considered relevant because the concept is often used to facilitate spatial reasoning (Woolcott et al., 2022). A total of three leading indicators are used regarding spatial reasoning skill, namely spatial perception, mental rotation, and spatial visualization. Spatial perception allows students to distinguish and identify geometric characteristics of objects through different perspectives (Hisyam et al., 2023). Mental rotation includes the ability to rotate objects in the mind without changing the shape or size (Ramful et al., 2017). Meanwhile, spatial visualization allows an individual to understand the relationship between objects and manipulate mental images (Evidiasari et al., 2019). In this context, developed media is oriented to the three aspects.

Learning process has been running actively and is student-centered. However, media is in the form of manipulative teaching aids and functions to show the elements of polyhedra, such as points, angles, edges, sides, space diagonals, side diagonals, etc. These manipulative teaching aids have limitations in terms of quantity and interactivity in providing an in-depth learning experience. In addition, digital learning media with the potential to support geometry learning are rarely used. The available student worksheets depend on learning resources from the government and have been integrated with the GeoGebra web. Even though the student worksheets can display geometric visual objects because of the integration with GeoGebra, the 3D objects are static and cannot be manipulated, such as rotated, resized, or transformed. The limitation reduces opportunities to explore geometric concepts dynamically. In the context of character, students are already proficient in using technology and some possess smartphones with the Android OS. The use of smartphones in schools is also allowed and students generally have access to the devices during learning. However, supporting infrastructure such as Wi-Fi networks in schools is still unavailable.

To overcome the problem, the ideal goal to be achieved is the development of digital media based on visual technology to understand the concept of polyhedra. Since the use of smartphones in schools is allowed, media developed is designed to be installed on mobile devices, such as smartphones or tablets. Due to the limited Wi-Fi network, this multimedia is used without requiring an internet connection. The application developed is dynamic, allowing interactive manipulation of 3D objects including rotation, scaling, and transformation to change object shape. To increase the appeal, learning experience is presented, resembling an adventure game, equipped with an explanation of the material through audio-visual (Wang, 2022). Reconstruction of the existing student worksheets was carried out by integrating AR technology to optimize the use of student worksheets (Lai &

Cheong, 2022; Wu et al., 2024). The AR selected was marker-based, where student worksheets as a printed book as a marker to trigger AR elements in the application.

The results of the needs analysis are a blueprint to design a flowchart for a MAR-based geometry learning media application known as GEMBI AR. This mobile application is in the form of an educational game containing geometry material designed to assist students in facilitating spatial reasoning. To support GEMBI AR, a printed book containing the target image or marker of game is provided. The book is equipped with teaching materials and geometry assignments at the lower secondary school level to help make it easier for students in the geometry learning process.

3.1.2. Design of MAR

The steps taken after needs analysis include 1) building a flowchart, 2) sketching media designs, 3) preparing and creating content materials, 4) combining content obtained in the Unity program, and 5) designing spatial reasoning skill test instrument based on previous indicators. The flowchart design can be seen in Figure 2 and the GEMBI AR application cannot stand alone. Therefore, learning media developed consists of two components, namely a printed book and the GEMBI AR application functioning as a marker and software, respectively.

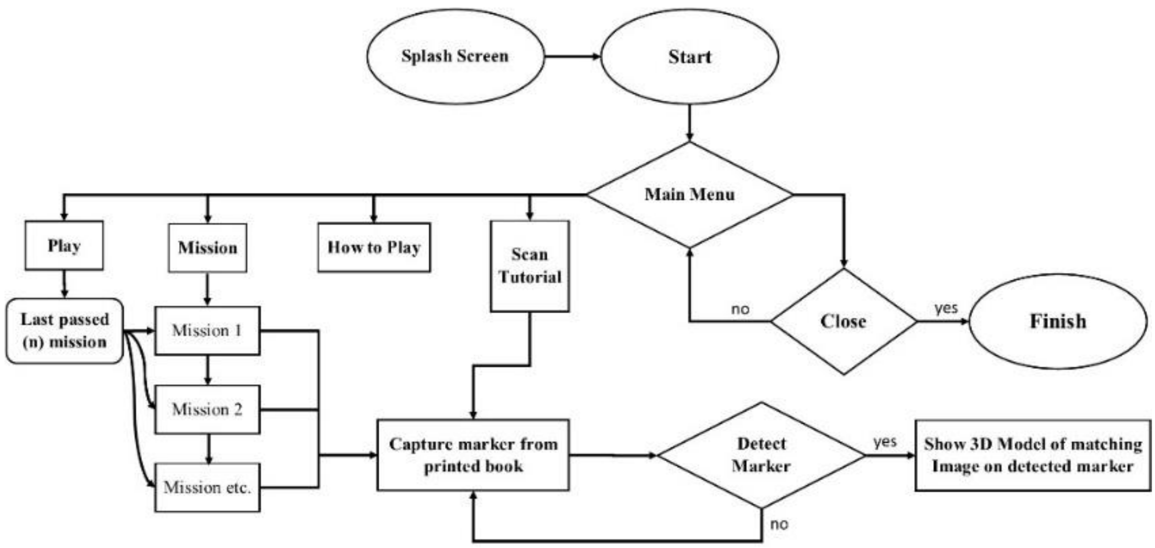


Figure 2. Flowchart of GEMBI AR

GEMBI AR is game designed to teach the concept of polyhedra geometry, including cubes, cuboids, pyramids, and prisms. Game consists of six missions to be completed by students. The first mission introduces the definition of polyhedra, with various types of pyramids and prisms based on the shape of the bases. Meanwhile, the second mission covers the elements of polyhedra, such as vertices, edges, faces, face diagonals, space diagonals, and plane diagonals. The third mission focuses on the nets of polyhedra, offering several nets for exploration. The fourth and fifth missions teach the calculation of surface area and volume of polyhedra, accompanied by animation simulations to show the process of deriving formulas. The sixth mission addresses the combined volume of polyhedra, where students face challenges from the narrator named as GEMBI. These challenges consist of problems related to the surface area and combined volume answered based on GEMBI explanations.

3.1.3. Development of GEMBI AR

GEMBI AR developed based on a flowchart is an augmented reality (AR)-based application that uses special markers or signs printed in the physical world to trigger interaction with digital content on the device screen integrated into the physical book. This physical book functions as a medium that stores AR markers on certain images in the worksheet. Meanwhile, 3D objects related to mathematical content, such as polyhedra, appear interactively on the device screen when the image is scanned. GEMBI AR and the physical book complement each other to provide the context or instructions needed to understand the material. The application enriches learning experience with interactive visualizations by showing relevant 3D objects. Students are also shown a three-dimensional visualization of geometric shapes in game. The shapes are manipulated in missions by rotating, enlarging, or shrinking. Moreover, the GEMBI AR application shows 3D objects, and students listen to explanations related to the material. Figures 3 and 4 present the results of this development.

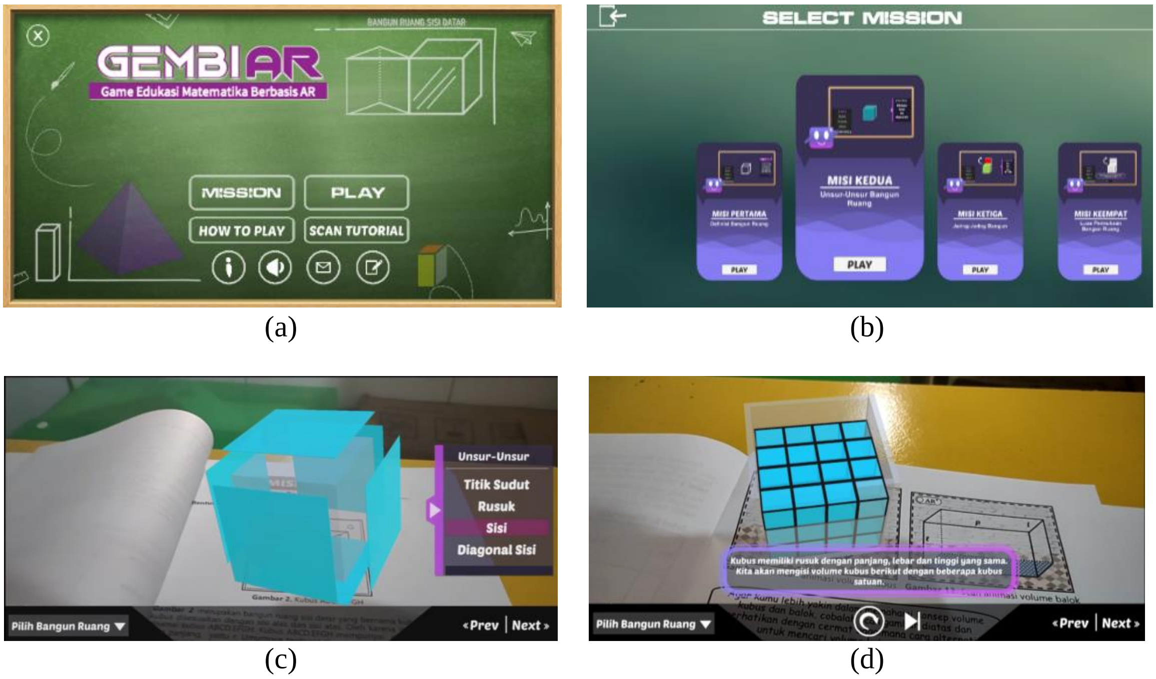
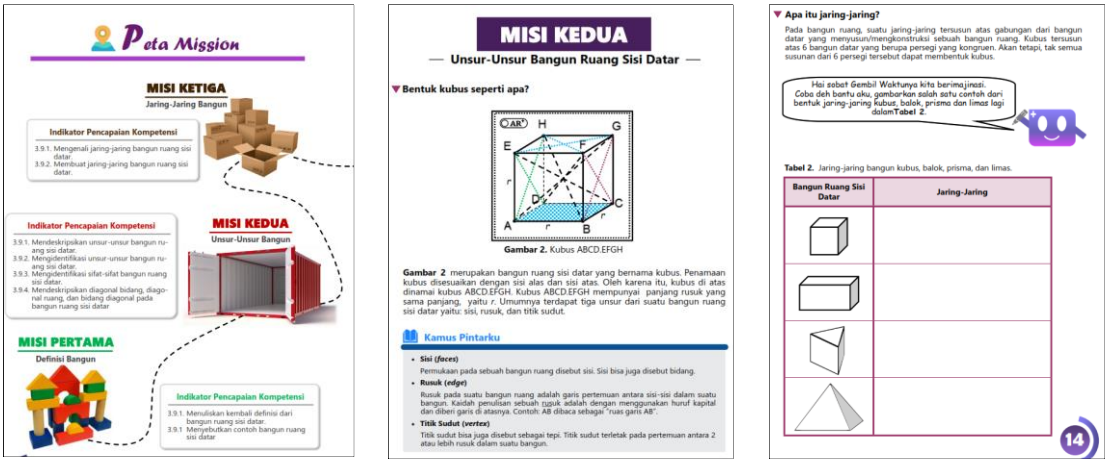


Figure 3. Display of the GEMBI AR game: (a) Main menu; (b) Mission menu; (c) Second mission page; (d) Fifth mission page



(a) (b) (c)

Figure 4. Display of the printed book model: (a) Table of contents; (b) The second mission page; (c) Activity guide in the book

Validation was carried out by CE and ME using a Likert scale questionnaire instrument to test the suitability of the media before it was used in learning activities. In this context, GEMBI AR is divided into applications and physical books. The following is a recapitulation of the results of the validity analysis obtained from the validation sheet (see Tables 3 and 4).

Table 3. Recapitulation of product validity based on CE

Aspects	Index of Aiken V	Criterion
Clarity of content	1.00	High Validity
Use of language that is easy for students to understand	1.00	High Validity
Suitability of the material presented	1.00	High Validity
Presentation of Content in Games	1.00	High Validity
Average Validity of GEMBI AR	**1.00**	**High Validity**

Table 4. Recapitulation of product validity based on ME

Aspects	Index of Aiken V	Criterion
Appropriateness of language to the student development stages	1.00	High Validity
The suitability of the game with the material presented	1.00	High Validity
Compatibility of game components	1.00	High Validity
Ease of use Navigation	0.98	High Validity
Average Validity of GEMBI AR	**0.995**	**High Validity**

Tables 3 and 4 show that the average values of the Aiken V index from three CE and ME are 1 and 0.995, with high validity criteria. Based on the perspectives of CE and ME, GEMBI AR meets the high validity criteria.

Table 5. Recapitulation of product validity for printed book

Aspects	Index of Aiken V	Criterion
Content of Material	1.00	High Validity
Completeness of Presentation	0.99	High Validity
Language Clarity	0.96	High Validity
Format Clarity	0.96	High Validity
Average Validity of GEMBI AR	**0.977**	**High Validity**

Table 5 shows that the average value of the Aiken V index from validators for printed books is 0.977. Therefore, the printed book for GEMBI AR also meets the valid criteria. Based on the description, the quality of media development products is considered very valid and feasible for implementation in schools.

3.1.4. Implementation of GEMBI AR in Geometry Learning

Trial and field testings were carried out in the implementation phase. In the initial phase, trial testing is used to evaluate the compatibility of media or application. Meanwhile, field testing is a further trial conducted in a real environment on a larger scale to review the quality of GEMBI AR in terms of practicality and effectiveness.

Trial testing was carried out in two phases consisting of black box and small group. Black box testing comprised two mathematics teachers to review the functions of the application. After black box testing with mathematics teachers, GEMBI AR was analyzed in a small group of four random eighth-grade students. This test evaluates the feasibility of the application from the perspective of the target users, specifically regarding the ease of use. The results of the trial testing showed that no bugs or internal errors were found, and the application was successfully installed on smartphones. So that field trials can be carried out. Trial testing activities can be seen in Figure 5.

(a) (b)

Figure 5. Black box testing activities with teachers and small group evaluation: (a) Black box testing activities with teachers; (b) Trials with a small group of students

The field test comprised 18 eighteenth-grade students of class 8A, who were selected based on ability to operate smartphones. First, a pre-test was conducted to measure spatial reasoning skill. Subsequently, students used GEMBI AR for three meetings with the topic of polyhedra. During learning activities, the teacher was also actively part of learning process in the classroom and could observe the application of the developed media. The direct inclusion of the teacher provided an assessment of the practicality of using learning media. At the end of the meeting, a practicality survey was conducted to assess user satisfaction after participating in geometry learning assisted by GEMBI AR media. The implementation activities in the classroom can be seen in Figure 6.

Figure 6. Implementation of GEMBI AR in geometry learning

3.1.5. Evaluation Stage

The practicality assessment of media was conducted by two mathematics teachers and students from A class. The instrument used was a practicality assessment tool with a Likert scale covering interface design, ease of operation, language clarity, relevance to learning materials, and satisfaction. The results of the recapitulation percentage of learning implementation were obtained at 87.7%. Learning carried out using GEMBI AR was manageable since the percentage of the results was above 80%. Furthermore, the percentage of the practicality score obtained from the responses of teachers and students is 96% and 91.7%, with a very practical category. The recapitulation of the practicality score can be seen in Table 6.

Based on the data from learning implementation sheet, the quality of the GEMBI AR media developed has met the very practicality criteria. Therefore, GEMBI AR can be implemented to learn mathematics, specifically geometry.

GEMBI AR was positively acknowledged and received by teachers and students as a geometry learning tool for polyhedra content. These results assured that the media developed was met the needs of target users, and expectations in providing solutions to overcome the challenges of limited digital learning media for learning. Considering the accessibility, GEMBI AR was designed to be mobile-based application that enables student to utilize it regardless of location and time. This application could be installed on a smartphone or tablet without requiring an internet connection. Thus, it can still be utilized by teachers and students in schools that have limited Wi-Fi network infrastructure. The results of this research also verify the validation of experts who state that GEMBI AR has met the criteria for high validity in terms of material, media, and the printed book. Thus, GEMBI AR can be used as an alternative digital learning media based on MAR technology that supports geometry learning.

Table 6. Recapitulation of teacher and student response feedback to GEMBI AR

Aspects	Average Score of Teacher Response	Average Score of Student Response
Interface Design	4.75	4.59
Ease of Operation	4.50	4.57
Language Clarity	5.00	4.57
Relevance to learning materials	4.75	4.58
Satisfaction with using the app	5.00	4.64
Mean scores	4.80	4.59
Percentage	96%	91.8%
Category	**Very Practical**	**Very Practical**

3.1.6. Impact of GEMBI AR on Students' Spatial Reasoning Skills

The objectives of developing learning media is to improve spatial reasoning skill. After using GEMBI AR for three meetings in geometry learning, students were given spatial reasoning skill test. Furthermore, a comparison was made between the initial and final test scores to determine when there was an increase in spatial reasoning skill. Figure 7 shows a graphical representation of pre-test and post-test spatial reasoning tests.

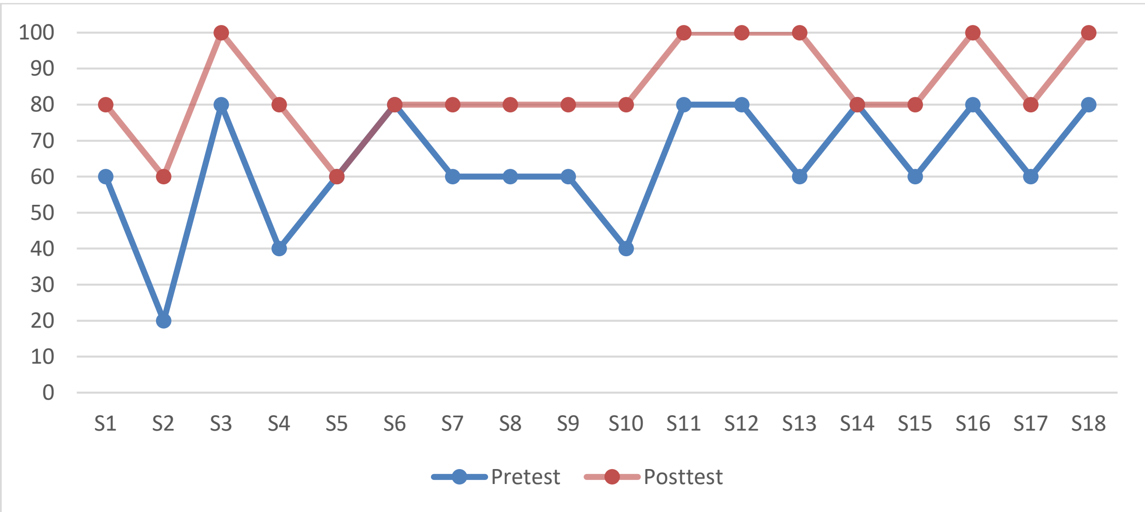


Figure 7. Students' spatial reasoning profiles

Based on Figure 7, a total of 15 students (83.33%) showed an improvement in scores from the pretest to the posttest. Since the percentage of score improvement results from the pretest to the posttest was above 80%, the intervention of using GEMBI AR media in geometry learning was applied to facilitate spatial reasoning skill.

Spatial reasoning skill before and after using the GEMBI AR application in geometry learning are compared. This analysis aims to identify the effectiveness of the application in facilitating spatial reasoning skill of lower secondary school students through inferential statistical tests. Comparative analysis testing starts by analyzing the normality of the data. In this research, the normality test used the one-sample Kolmogorov-Smirnov test with the SPSS program. Table 7 presents the pre-test and post-test normality tests of spatial reasoning skill to be 0.003 and 0.000, respectively.

Table 7. Tests of Normality

Test		Kolmogorov-Smirnov		
		Statistic	**df**	**Sig.**
Score	Pretest	0.256	18	0.003
	Posttest	0.301	18	0.000

Based on the results obtained in Table 7, the data received is not normally distributed. Therefore, a non-parametric test using the Wilcoxon test was used (see Table 8).

Table 8. Wilcoxon test results

	Posttest - Pretest
Z	-3.578[b]
Asymp. Sig. (2-tailed)	0.000

b. Based on negative ranks.

Wilcoxon test shows a significant difference between the average spatial reasoning scores before and after using GEMBI AR (Asymp.Sig.(2-tailed) = 0.000 < 0.05) (see Table 8). Therefore, GEMBI AR applications affect spatial reasoning of students.

The mean (M) and standard deviation (SD) of spatial reasoning skill for pre-test and post-test scores are 63.33 and 84.44, with SD of 17.150 and 12.935, respectively.

Table 9. Pre-test and post-test data results

	N	**Mean**	**Std. Deviation**	**Std. Error Mean**	**N-Gain**	**Category**
Pretest	18	63.33	17.150	4.042	0.576	Moderate
Posttest	18	84.44	12.935	3.049		

Based on Table 9, spatial reasoning skill increase after using GEMBI AR in geometry learning. The data shows an increase in the classical average scores, with values rising from 63.33 before to 84.44 after. Therefore, the N-Gain score was 0.576 with a moderate category. Thus, it can be concluded that the use of GEMBI AR is quite effective in improving students' spatial reasoning skills (Meltzer, 2002). This improvement shows that the use of GEMBI AR directly facilitates the development of students' skills in visualizing and understanding the relationship between shape and space, thereby supporting the improvement of students' understanding of geometric concepts (Mulligan, 2015; Otálora & Taborda-Osorio, 2025). N-

Gain testing was carried out to review influential aspects related to the intervention using GEMBI AR.

Table 10. Recapitulation of students' spatial reasoning profiles

Aspects	Average Score		N-Gain	Category
	Before	After		
Spatial Perception	55.56	100.00	1.00*	High
Mental Rotation	55.56	77.78	0.50	Moderate
Spatial Visualization	88.89	91.67	0.25	Low

Table 10 shows improvements in each aspect of spatial reasoning influencing spatial reasoning test scores. The highest increase occurred in spatial perception, with the average score increasing from 55.56 to 100.00 and an N-Gain of 1.00 (high category). Mental rotation also improved with scores rising from 55.56 to 77.78 and an N-Gain of 0.50 (moderate category). Conversely, Spatial visualization demonstrated only a slight improvement, increasing from 88.89 to 91.67 with an N-Gain of 0.25 (low category). Overall, the data showed an increase in each aspect of students' spatial reasoning, which contributed to their improved spatial ability test results. However, the spatial perception aspect showed the highest increase which contributed to the enhancement of students' spatial ability test scores after using the GEMBI AR application. An illustration of the graph comparing the scores before and after using GEMBI AR is presented in Figure 8. Thus, it can be said that geometry teaching supported by GEMBI AR improves spatial reasoning skill. Therefore, GEMBI AR as a developed learning media can be considered successful in achieving its development objectives.

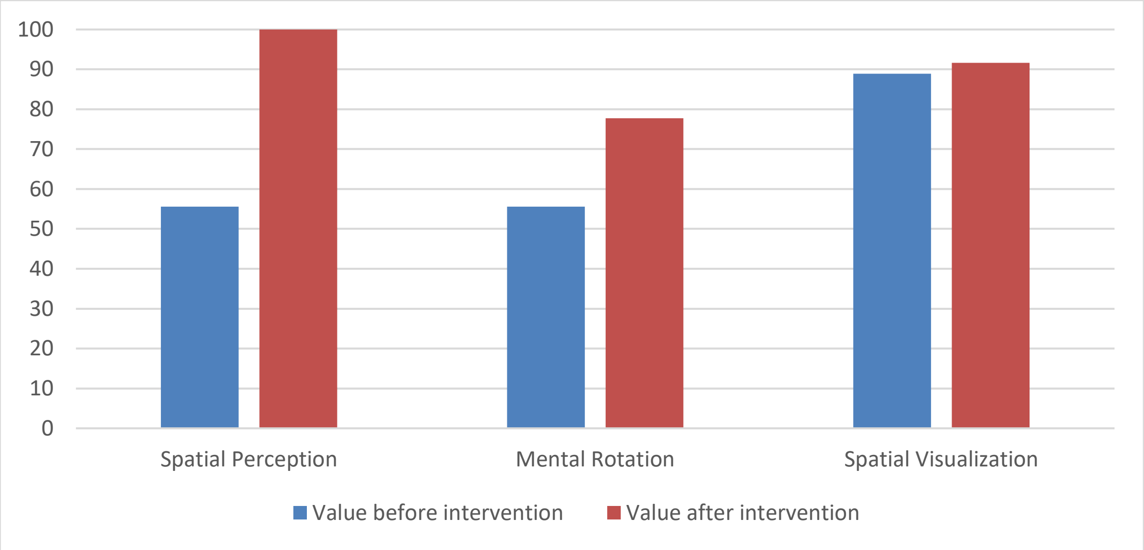


Figure 8. Comparison of students' spatial reasoning skills before and after using GEMBI AR

3.2. Discussion

The product of this R&D is an application called GEMBI AR. The AR-based mobile educational game focuses on geometry learning regarding the concept of polyhedra to improve spatial reasoning in the moderate category. Development process started with a literature review, field observation, and interviews with teachers to ensure user needs. GEMBI AR focuses on the main concepts of polyhedra including definitions, elements, nets, surface area, volume, and the combination of surface area and volume of polyhedra. To support the optimization, this application is equipped with a printed book containing worksheets integrated with AR technology. The printed book contains a target image or marker that functions as a trigger in showing digital content. Development of GEMBI AR and the physical books have been validated by experts to ensure the developed products are consistent with the objectives. The average value of the Aiken V index for application validity by CE, ME, and printed books is 1, 0.995, and 0.977 in the high validity category. The results show that GEMBI AR is designed with content and media appropriate for the needs of students. This high validity also confirms that the application and printed books have met quality standards in terms of content relevance and media feasibility.

The use of GEMBI AR in geometry learning provides a unique opportunity, where students can determine various objects virtually without physical space limitations. The application allows students to view 3D models of polyhedron such as cubes, cuboids, prism, and pyramids rotated 360 degrees, as well as manipulate 3D shapes into nets by opening and closing objects virtually. Interactive animations are also provided in the form of learning video clips that guide in understanding the concept of surface area and volume of various polyhedra. The presentation of content through animated video clips helped students understand the steps to formulate the concept of surface area and volume better. Cohen and Hegarty (2014) explained that the use of animated learning videos provided a new atmosphere. The addition of the features is needed to create a more engaging immersive learning experience (Agrawal et al., 2020). Furthermore, students are given the task of solving problems based on interactive animated video clips. This feature creates challenges that enable students to apply the concepts, practice critical reasoning, hone spatial reasoning, and improve understanding of polyhedra. Nindiasari et al. (2024) added that AR applications visualized the exercise steps clearly to support the understanding of geometric concepts. The flexibility allows learning anytime according to availability. Through the various features explained, this application has a direct impact on supporting geometry learning to improve conceptual understanding and helping students achieve better learning outcomes.

The results of research on satisfaction with the use of GEMBI AR in geometry learning show a good level of satisfaction. Teachers and students feel interested and impressed to use virtual technology actively to support learning. This application can simplify polyhedra content with easy-to-understand language, user-friendly design, and ease of use. In addition, geometry content about polyhedra is assessed anytime and anywhere without an internet connection, contributing to a very high level of satisfaction, with an average score of 4.64 out of 5. Shaukat (2023) showed that AR technology was an innovation in presenting concepts without using real objects. This increases interest and allows students to easily access applications on mobile to enhance the efficiency of learning process.

Based on the description above, teaching assisted by virtual technology produces better learning outcomes compared to traditional methods (Magomadov, 2020; Prasetya et al., 2024; Su et al., 2022). The use of media integrated with technology provides more optimal achievement compared to traditional manipulative media (Hanggara et al., 2024; Wang, 2022). Given the increasing use of devices such as computers, smartphones, and tablets among students, understanding the impact of technology on spatial skill is very important. Septia et al. (2018) stated that the potential of AR in presenting 3D objects, such as building shapes or spatial animations helped students improve spatial reasoning skill. The results showed a statistically significant difference between spatial reasoning skill scores before and after using GEMBI AR in geometry learning (Sig.<0.05). Therefore, GEMBI AR has an effect on spatial reasoning skill of students. This finding confirms the results of previous studies which stated that students' spatial reasoning abilities can be improved by using virtual technology-based media (Lowrie et al., 2021; Septia et al., 2018; Woolcott et al., 2022). Data analysis showed an increase in the average score of spatial skill from 63.33 before using the application to 84.44, with an N-Gain score of 0.576 in the moderate category. The results statistically resulted in an increase in spatial reasoning skill after the intervention using GEMBI AR. This reports the potential of GEMBI AR in supporting spatial reasoning skill.

GEMBI AR supports three main components in spatial reasoning, namely spatial perception, mental rotation, and spatial visualization. Spatial perception is enhanced through the lean touch feature, which allows students to manipulate 3D objects, such as rotating and changing the viewing angle, to help students better understand the position and orientation of objects, with an N-Gain increase of 1 in the high category. In addition, the lean touch feature also indirectly supports mental rotation by providing students with direct experience in manipulating 3D objects, which trains their ability to imagine the rotation or change of object position. Mental rotation is also supported by the automatic rotation animation feature, with an N-Gain increase of 0.5 in the moderate category. Meanwhile, spatial visualization is facilitated by a 3D visualization feature allowing students to determine changes in the shape of objects, such as turning objects into nets. However, the increase in spatial visualization was obtained at an N-Gain of 0.25 in the low category, showing that more specific additional activities are needed to maximize this skill. Overall, GEMBI AR can facilitate three aspects comprehensively, contributing positively to improving spatial reasoning skill.

4. CONCLUSION

Development of geometry learning media based on MAR oriented towards spatial reasoning skill was successfully developed by ADDIE model procedure. The resulting media was named “GEMBI AR” learning game, equipped with a printed book. Based on data analysis, the validity aspects for GEMBI AR and the printed book consisted of high validity criteria. As for the practical aspects, the average percentage scores from mathematics teachers and students were 96% and 91.8%, respectively. In the effectiveness analysis, the Wilcoxon test showed an effect of GEMBI AR on spatial reasoning. The test results showed a relatively significant increase in the average score before and after using GEMBI AR of

63.33 and 84.44. The N-Gain score was 0.576 with a moderate category and the outcomes in geometry learning significantly facilitated spatial reasoning skill. Therefore, GEMBI AR met the quality of development requirements regarding validity, practicality, and effectiveness in promoting spatial reasoning skill.

This research succeeded in developing a product facilitating spatial reasoning skill. However, several limitations need to be considered in terms of optimizing features to support spatial visualization skill and involving a control group in the research design. In addition, this study is also limited to an inadequate sample size. An extensive research sample including several students from various schools should be used as participants. For further research, it is recommended to develop more specific features to provide additional insights in understanding the improvement of overall spatial reasoning skills. Involving a control group, both with and without manipulative media, is also required to evaluate the effectiveness of this application more objectively. In addition, a wider research sample is needed by involving students from various schools as participants. The addition of aspects, indicators, or test items to the test instrument is also needed to ensure that the test results can accurately represent students' spatial reasoning skills. Nevertheless, this study has confirmed that the use of mobile-based augmented reality (MAR) technology in the classroom can improve students' spatial reasoning skills on a limited scale.

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Declarations

Author Contribution	: ASM: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, and Writing - original draft; LA: Funding acquisition, Investigation, Methodology, Supervision, Visualization, and Writing - original draft; CS: Investigation, Methodology, Supervision, and Writing - original draft; HZ: Methodology, Validation, and Writing – review & editing.
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Conflict of Interest	: The authors declare no conflict of interest.
Additional Information	: Additional information is available for this paper.

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