



## Fostering students' spatial ability in learning polyhedra using augmented reality-based android 3D interactive learning media

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### Abstract

**Background:** The low level of spatial ability is one of the main factors contributing to students' difficulty in understanding geometry, particularly polyhedra. This difficulty is evident in recognizing shapes, visualizing shape transformations and rotations of objects, understanding the relationships between parts of an object, and determining the relative positions of objects

**Aims:** The purpose of this study is to describe the process of developing a 3D interactive learning tool based on augmented reality for an Android app, featuring polyhedra content that supports the development of valid, practical, and effective spatial ability.

**Methods:** This research method employs the Research and Development approach using the ADDIE model (Analysis, Design, Development, Implementation, and Evaluation) proposed by Dick and Cary.

**Result:** The results of this study show that in the needs and problem analysis phase, issues were identified through observation and interviews. The design phase included developing learning objectives, scenarios, media design, content, and assessment tools based on the analysis results. In the development stage, the initial design was transformed into a product validated by experts, achieving 78.4% from media experts and 78.8% from content experts. During implementation, the media was applied and obtained an 81.9% practicality rating and 81.25% effectiveness, indicating its effectiveness in enhancing students' spatial ability in polyhedra material. The evaluation phase further analyzed student responses comprehensively.

**Conclusion:** Based on this description, it can be concluded that the 3D Android application is valid, practical, and effective for use in learning.

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## INTRODUCTION

Mathematics education plays a crucial role in developing students' cognitive abilities, particularly in understanding abstract concepts such as geometry. Among various mathematical competencies, spatial ability has been recognized as a fundamental skill that supports students in interpreting and manipulating three-dimensional objects (Ho et al., 2006; Medina Herrera et al., 2019; Pittalis & Christou, 2010). Spatial ability encompasses multiple components, including spatial perception, spatial visualization, mental rotation, spatial relations, and spatial orientation, all of which are essential for solving geometry problems (Nagy-Kondor, 2017; Porat & Ceobanu, 2023). In the context of polyhedra learning, these abilities enable students to understand the structure, relationships, and transformations of geometric objects more effectively. However, despite its importance, spatial ability remains a challenging aspect for many students in secondary education. This issue is particularly evident in topics involving three-dimensional representations, where

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students must mentally construct and manipulate objects that are not directly observable. Consequently, improving students' spatial ability has become a significant concern in contemporary mathematics education. Therefore, innovative instructional approaches are needed to facilitate students' understanding of complex geometric concepts.

Empirical evidence indicates that students often experience difficulties in learning polyhedra due to their limited ability to visualize and interpret spatial relationships. Studies have shown that students struggle with tasks such as constructing nets, identifying geometric elements, and determining surface area and volume (İbili et al., 2020; Lehmann, 2023). These difficulties are frequently associated with insufficient exposure to interactive and visual learning experiences that can support spatial reasoning. In many classrooms, traditional teaching methods still rely heavily on static images, textbooks, or teacher explanations, which may not adequately represent three-dimensional concepts (Teplá et al., 2022; Triepels et al., 2020). As a result, students tend to develop fragmented understanding and misconceptions about geometric structures. Observations in real classroom settings further suggest that such conventional approaches may limit students' engagement and participation, as they provide minimal opportunities for interactive and exploratory learning. This limitation reduces students' ability to examine geometric objects from multiple perspectives, which is essential for developing spatial ability. Therefore, there is a clear need for more dynamic and student-centered learning approaches, particularly through the integration of interactive technologies that enable direct manipulation and visualization of three-dimensional objects.

The rapid advancement of digital technology has opened new possibilities for transforming mathematics learning into a more interactive and engaging experience. One promising technology in this context is Augmented Reality (AR), which enables the integration of virtual objects into real-world environments in real time (Arena et al., 2022; Jo & Kim, 2019; Syed et al., 2023). AR has the potential to bridge the gap between abstract mathematical concepts and concrete visual representations, thereby enhancing students' conceptual understanding (Özdemir & Özçakır, 2026). Through AR, students can interact with three-dimensional objects, manipulate them, and observe their transformations directly, which supports the development of spatial skills. Moreover, AR-based learning environments can foster active learning by encouraging exploration, experimentation, and discovery (Li et al., 2025). The use of mobile devices, particularly Android-based applications, further increases the accessibility and practicality of AR in educational settings (Zulfiqar et al., 2023). This technological integration aligns with the demands of 21st-century learning, which emphasize digital literacy and student-centered pedagogy. As such, AR represents a relevant and innovative approach to addressing challenges in geometry learning. Therefore, innovative instructional approaches that leverage interactive and immersive technologies, particularly Augmented Reality (AR), are needed to facilitate students' understanding of complex geometric concepts, as such technologies enable real-time visualization, manipulation, and exploration of three-dimensional objects that are otherwise difficult to conceptualize through conventional instruction.

The urgency of implementing technology-enhanced learning is further reinforced by the increasing demand for meaningful and contextual learning experiences (Yu, 2022). In the current educational landscape, students are expected not only to understand concepts but also to apply them in real-life situations (O'Neill & Short, 2025; Sujatha & Vinayakan, 2023). However, the gap between theoretical knowledge and practical application remains a persistent issue in mathematics education. Traditional instructional methods often fail to provide meaningful contexts that connect abstract concepts with real-world experiences. As a result, students may perceive mathematics as difficult and irrelevant to their daily lives. The integration of AR technology offers an opportunity to create immersive learning environments that make abstract concepts more tangible and relatable. Additionally, AR can support differentiated learning by accommodating diverse student needs and

learning styles. This approach also encourages independent learning, as students can explore materials at their own pace and revisit concepts as needed. Therefore, the development of AR-based learning media is not only relevant but also necessary to improve the quality of mathematics education. In this context, research focusing on AR integration becomes increasingly important.

Previous studies have explored the use of Augmented Reality in mathematics and science education, particularly in enhancing spatial ability and conceptual understanding. For instance, Chen and Chen (2022) found that AR significantly improved students' spatial ability and academic achievement in technical drawing courses. Similarly, Wu et al. (2024) reported that AR applications positively influenced students' cognitive load, attitudes, and spatial perception in science learning. In the field of geometry, Supli and Yan (2024) demonstrated that mobile AR-based learning games could effectively facilitate students' spatial reasoning. Other studies, such as those by Uriarte-Portillo et al. (2023), highlighted the potential of intelligent AR systems in supporting geometry learning through interactive visualization. Furthermore, Tarng et al. (2024) emphasized the importance of dimensionality in AR-based learning environments, showing that immersive technologies can enhance students' understanding of geometric concepts. Despite these promising findings, several critical gaps remain insufficiently addressed in the existing literature. First, most studies on Augmented Reality (AR) in mathematics education tend to focus on general geometry concepts without addressing specific and conceptually demanding topics such as polyhedra, which require a higher level of spatial reasoning. Consequently, the role of AR in supporting spatial ability within well-defined mathematical content domains remains limited and lacks empirical depth. Second, although AR applications are often described as interactive, many existing implementations provide only limited forms of interaction, such as static visualization or basic object manipulation, without systematically supporting key components of spatial ability, including mental rotation, spatial relations, and spatial orientation. This reflects a misalignment between AR design features and theoretically grounded spatial ability constructs. Third, prior research has largely emphasized learning outcomes or student engagement, while offering limited insight into how AR-based learning media are systematically designed to integrate cognitive objectives, instructional strategies, and spatial ability development within a coherent instructional framework. Therefore, although AR has been widely recognized as a valuable learning tool, there is a pressing need for research that not only applies AR in specific mathematical contexts (particularly in polyhedra learning) but also explicitly integrates spatial ability indicators into both the design and evaluation of interactive learning media to ensure meaningful and theoretically grounded learning outcomes.

In addition to the limitations in content specificity, previous studies also reveal methodological gaps in the development and evaluation of AR-based learning media. Many studies emphasize the effectiveness of AR in improving learning outcomes but provide limited insights into the systematic development process of the media (Tian & Ironsi, 2025; Trisnawati et al., 2025). Moreover, the integration of spatial ability indicators into AR-based learning design is often not explicitly addressed, resulting in a lack of alignment between instructional objectives and learning activities. Some studies also focus primarily on student motivation and engagement without thoroughly examining cognitive outcomes related to spatial reasoning (Harris, 2023; Lowrie et al., 2019). Furthermore, there is a lack of comprehensive evaluation that simultaneously considers validity, practicality, and effectiveness of the developed media. This gap indicates the need for research that not only develops AR-based learning tools but also evaluates them using a systematic and rigorous framework. The ADDIE model offers a structured approach that can address these limitations by integrating analysis, design, development, implementation, and evaluation. Therefore, a study that combines AR technology with a systematic development model and explicit spatial ability indicators is necessary. This approach is expected to contribute to both theoretical and practical advancements in mathematics education.

Based on the identified gaps, this study aims to develop and evaluate a 3D interactive learning medium based on Augmented Reality for Android applications to support students' spatial ability in learning polyhedra. Specifically, this study seeks to describe the development process of the learning media using the ADDIE model and to assess its validity, practicality, and effectiveness. The novelty of this study lies in the integration of comprehensive spatial ability indicators into the design of AR-based learning media, focusing specifically on polyhedra content. Unlike previous studies, this research provides a detailed development framework and a systematic evaluation of the media across multiple dimensions. Theoretically, this study contributes to the literature by offering a model for integrating AR technology with spatial ability development in mathematics education. Practically, it provides educators with an innovative and accessible tool to enhance students' understanding of three-dimensional geometry. Furthermore, this study supports the implementation of technology-enhanced learning aligned with the demands of 21st-century education. By addressing both conceptual and practical challenges, this research is expected to improve the quality of geometry learning. Ultimately, the findings of this study may serve as a reference for future research and development of AR-based learning media in mathematics education.

## METHOD

### Research Design

This study employed a Research and Development (R&D) approach aimed at developing and evaluating a 3D interactive learning medium based on Augmented Reality (AR) to support students' spatial ability in learning polyhedra. The R&D approach was selected because the primary objective of the study was not only to examine learning outcomes but also to produce a valid, practical, and effective educational product. The development process followed the ADDIE model, which consists of five systematic phases: Analysis, Design, Development, Implementation, and Evaluation. This model was chosen due to its structured and iterative nature, allowing continuous refinement at each stage to ensure product quality and instructional effectiveness. Furthermore, the ADDIE framework supports formative evaluation throughout the development process, making it suitable for instructional media design. The use of this model ensures that the resulting product is systematically developed and empirically evaluated. Therefore, the R&D approach using the ADDIE model aligns with the objectives of this study.

### Research Setting and Time

The study was conducted at a junior high school in Batu City, Indonesia, during the second semester of the 2024/2025 academic year, from January to March 2025. The school implements the Merdeka Curriculum, which emphasizes student-centered and technology-integrated learning. This setting was selected based on preliminary observations indicating limited use of interactive digital learning media in geometry instruction. The timing of the study was aligned with the teaching schedule of polyhedra material to ensure contextual relevance. The classroom environment provided an authentic setting for implementing and evaluating the developed AR-based learning media. Additionally, students' access to Android devices supported the feasibility of using AR technology. Therefore, the selected setting and timeframe were appropriate for achieving the research objectives.

### Population and Participants

The population of this study consisted of all eighth-grade students at the selected school. The sample included 32 students, selected using a purposive sampling technique based on specific inclusion criteria. These criteria included students who were currently studying polyhedra, had access to Android devices, and were willing to participate in the study. The purposive sampling approach ensured that participants were relevant to the research objectives and capable of engaging

with the developed media. The sample size is consistent with R&D studies, which emphasize product development and initial validation rather than generalization. The selected participants represented typical classroom conditions, allowing for realistic evaluation of the learning media. Therefore, the sample was considered appropriate for assessing validity, practicality, and effectiveness.

### Research Instruments

The instruments used in this study consisted of both non-test and test instruments. The non-test instruments included a student response questionnaire, validation sheets, and instructional modules. The student response questionnaire was designed to measure the practicality of the learning media, covering aspects such as content relevance, interactivity, usability, and student engagement. The validation sheets were used by experts to assess the quality of the developed media in terms of design, content accuracy, language clarity, and instructional suitability. The test instrument consisted of a spatial ability test in the form of multiple-choice questions, developed based on five indicators: spatial perception, spatial visualization, mental rotation, spatial relations, and spatial orientation. These indicators were adapted from established spatial ability frameworks and aligned with polyhedra learning objectives. The detailed operational definitions of these indicators are presented in Table 1. The use of multiple instruments enabled comprehensive data collection from both cognitive and experiential perspectives.

**Table 1.** Spatial Ability Indicators

<b>Spatial Ability Indicators</b>	<b>Operational Description</b>
Spatial Perception	Students are able to identify polyhedra (cubes, beam, prisms, pyramids) based on different Augmented Reality representations.
Spatial Visualization	Students are able to visualize changes in the shape of polyhedra—including nets, elements, surface area, and volume based on Augmented Reality.
Mental Rotation	Students are able to predict the appearance of polyhedra and determine the position of the elements of a three-dimensional shape based on changes in Augmented Reality orientation.
Spatial Relations	Students are able to determine the relationships between the elements of polyhedra (faces, edges, vertices) as well as surface area and volume based on Augmented Reality.
Spatial orientation	Students are able to determine the position of the elements of polyhedra based on the viewpoint when the object is visualized through Augmented Reality.

### Validity and Reliability of Instruments

The validity of the instruments was established through expert judgment, involving a mathematics education lecturer acting as both a media and content expert. The validation process assessed the relevance, clarity, and appropriateness of the instruments. The results were quantified using percentage scores and interpreted based on validity criteria presented in Table 2.

**Table 2.** Product Validity Criteria

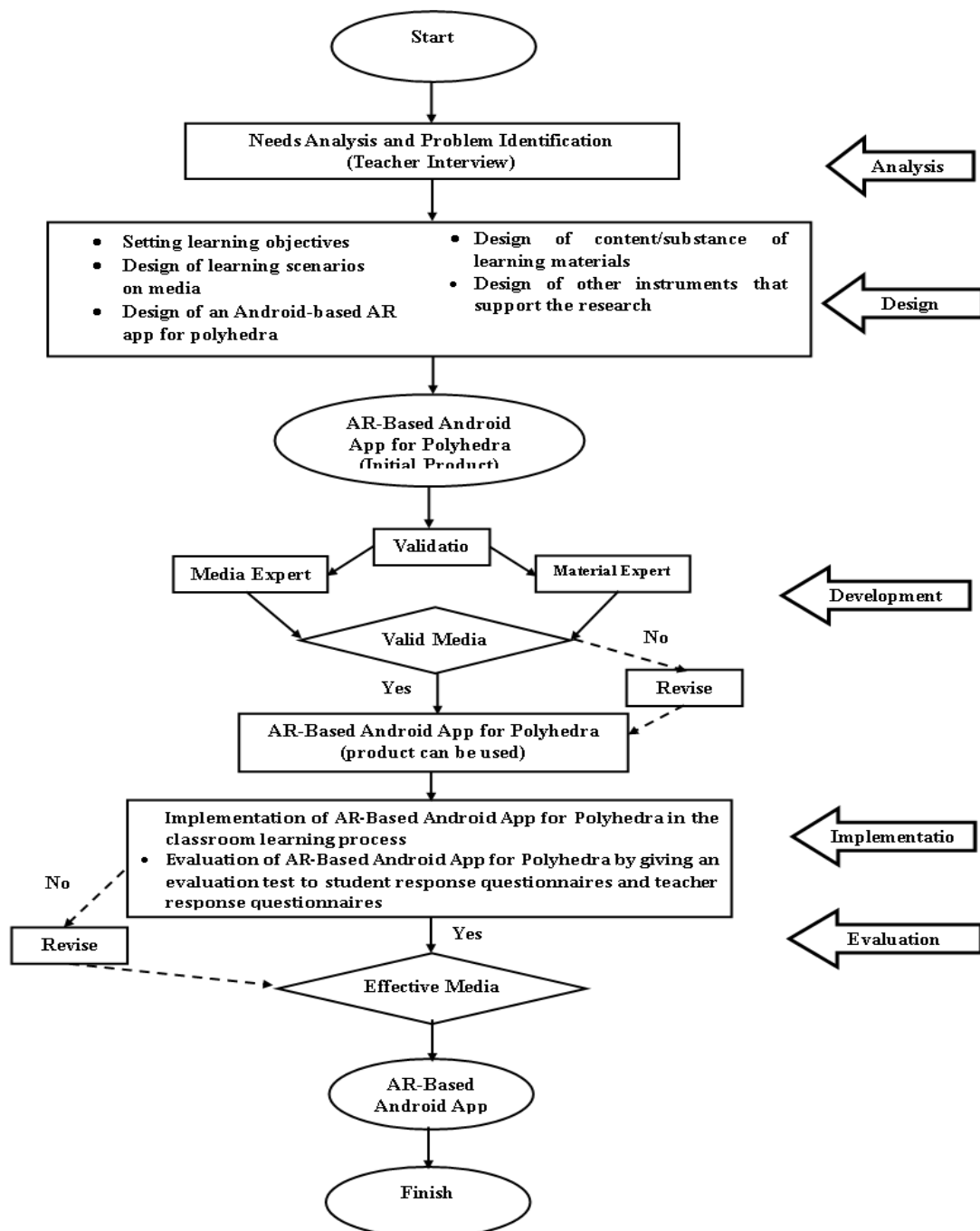
<b>Percentage Score</b>	<b>Validity Criteria</b>
00,00% – 20,00%	Very Invalid
21,00% – 40,00%	Invalid
41,00% – 60,00%	Moderately Valid
61,00% – 80,00%	Valid
81,00% – 100,00%	Highly Valid

To ensure reliability, the student response questionnaire was tested using Cronbach's alpha, with a coefficient of  $\geq 0.70$  considered acceptable. This analysis ensured the internal consistency of the instrument. Additionally, the spatial ability test was reviewed to ensure alignment with the defined indicators, supporting construct validity. These procedures ensured that the instruments were both valid and reliable for research purposes.

**Data Collection Procedures**

Data collection was conducted following the ADDIE stages. In the analysis phase, data were collected through observation, interviews, and questionnaires to identify learning needs. In the design phase, learning objectives, instructional scenarios, and media prototypes were developed. During the development phase, the AR-based media was created and validated by experts.

In the implementation phase, the media was applied in a classroom setting, where students engaged in learning activities using the AR application. After the learning session, students completed the spatial ability test and the response questionnaire. Finally, in the evaluation phase, all collected data were analyzed to assess the quality of the developed media. The overall development process is illustrated in Figure 1 (Development Flowchart). This systematic procedure ensured that the study was conducted in a structured and replicable manner.



**Figure 1.** Development Flowchart

### Data Analysis Techniques

Data analysis in this study employed descriptive quantitative methods to evaluate validity, practicality, and effectiveness. The validity and practicality scores were calculated using the following percentage formula:

$$P = \frac{\sum X}{\sum X_{\max}} \times 100\%$$

where “ $P$ ” represents the percentage score,  $\sum X$  is the total score obtained from respondents or validators, and  $\sum X_{\max}$  is the maximum possible score. The results were interpreted based on predefined criteria presented in Table 2 (Validity Criteria) and Table 3 (Practicality Criteria).

To measure the effectiveness of the learning media, the percentage of students who achieved the Minimum Passing Score (MPS) of 77 was calculated using the following formula:

$$E = \frac{n}{N} \times 100\%$$

where “ $E$ ” represents the effectiveness percentage,  $n$  is the number of students who achieved scores  $\geq 77$ , and  $N$  is the total number of students. The learning media was considered effective if at least 80% of students met the MPS criterion. All data were processed using spreadsheet-based calculations to ensure accuracy and consistency. This analytical approach was appropriate for R&D studies focusing on product evaluation rather than inferential statistical testing.

## RESULTS AND DISCUSSION

### Results

This study resulted in the development of an Augmented Reality (AR)-based 3D interactive learning media designed to support students' spatial ability in learning polyhedra. The findings are presented based on the ADDIE development stages, with emphasis on empirical results and their pedagogical implications.

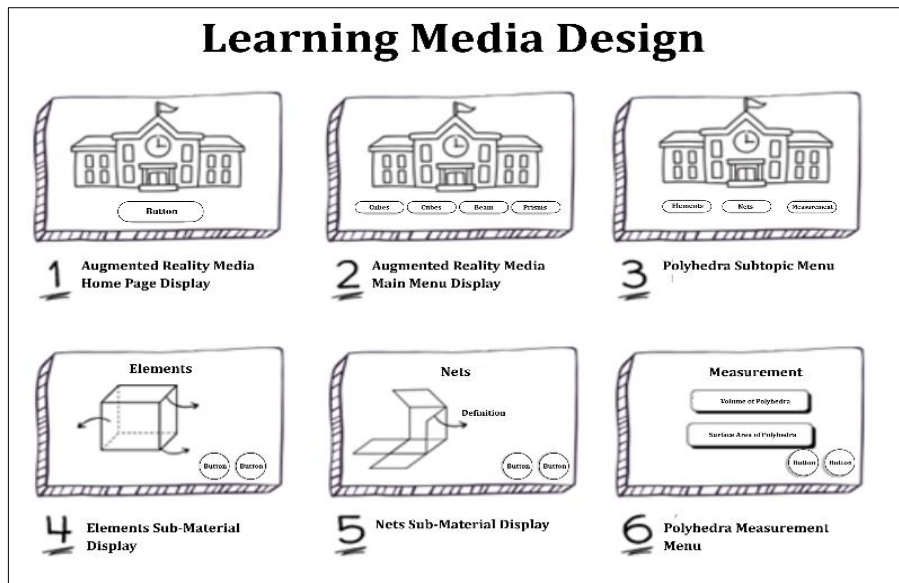
### Analysis Results

The needs analysis revealed several critical challenges in the existing learning process. Classroom observations and teacher interviews indicated that instruction was predominantly conducted using video-based media, resulting in passive learning and limited student interaction. This condition restricted students' opportunities to explore and manipulate geometric objects, which are essential processes in developing spatial ability.

Furthermore, students experienced difficulties in understanding polyhedra concepts, particularly in visualizing three-dimensional structures, identifying geometric elements, and interpreting spatial relationships. These findings indicate that students' spatial ability was insufficiently developed, primarily due to the lack of interactive and visual learning media. Therefore, the integration of AR-based learning media was identified as a relevant instructional solution to address these limitations.

### Design Results

Based on the identified needs, the learning media was designed to align with key spatial ability indicators, including spatial perception, spatial visualization, mental rotation, spatial relations, and spatial orientation. The design process resulted in a structured storyboard (Figure 2), which integrates interactive features such as object manipulation, multi-perspective visualization, and contextual learning tasks.



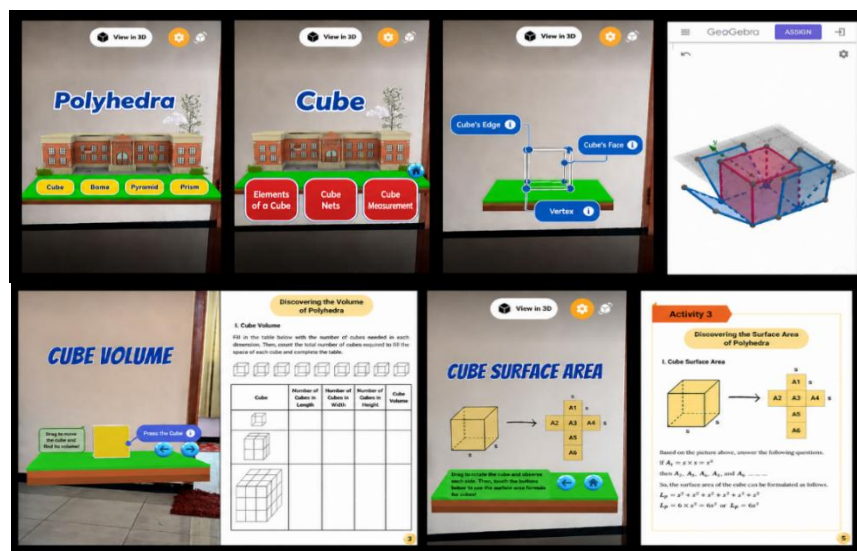
**Figure 2.** Examples of Storyboards for 3D Interactive Augmented Reality-Based Educational Media on an Android App

Figure 2 illustrates that each component of the storyboard is systematically organized to support progressive cognitive processes, from recognizing geometric shapes to performing complex spatial transformations. The inclusion of interactive elements reflects a constructivist learning approach, enabling students to actively engage with three-dimensional objects and construct their own understanding through exploration.

In addition to the media design, supporting instruments were developed, including instructional modules, a spatial ability test blueprint, and a student response questionnaire. These components were designed to ensure alignment between learning objectives, instructional activities, and assessment strategies.

**Development Results**

The development stage produced a functional AR-based 3D interactive learning application that includes polyhedra materials such as cubes, cuboids, prisms, and pyramids (Figure 3). The media integrates features that allow students to manipulate objects dynamically, observe geometric structures from multiple perspectives, and explore relationships between faces, edges, and vertices.



**Figure 3.** Examples of 3D Interactive Augmented Reality-Based Educational Media Displays on an Android App

Figure 3 demonstrates how the AR environment enables real-time interaction with virtual objects, thereby supporting spatial visualization and mental rotation skills. The integration of measurement concepts, such as surface area and volume, further facilitates the development of spatial relations and conceptual understanding.

The validity of the developed media was evaluated by experts. The results showed that:

- Media validity score: 78.4%
- Content validity score: 78.8%

Both scores fall within the valid category, indicating that the media meets acceptable standards in terms of design quality, content accuracy, and usability. However, expert feedback indicated that the media requires further enhancement in its constructivist elements, particularly in promoting deeper learner interaction and independent knowledge construction.

### Implementation Results

The implementation involved 32 eighth-grade students who engaged with the AR-based learning media in a classroom setting. Following the learning activities, students completed a response questionnaire to assess the practicality of the media.

The total questionnaire score was 1048 out of a maximum of 1280, resulting in a practicality level of 81.9%, which is categorized as highly practical. To provide additional statistical insight, the mean score per student was calculated as follows:

- Mean score = 32.75 out of 40
- Normalized mean = 0.82 (82%)

These results indicate that students perceived the media as engaging, easy to use, and supportive of their learning process.

The effectiveness of the media was evaluated based on students' achievement of the Minimum Passing Score (MPS = 77). The results showed that 26 out of 32 students (81.25%) achieved the expected learning outcomes. This finding suggests that the majority of students were able to understand polyhedra concepts successfully after using the AR-based media.

### Evaluation Results

The evaluation phase provided further insights into the strengths and limitations of the developed media. Student responses indicated increased engagement and participation, reflecting a positive affective impact of the AR-based learning environment. However, several constraints were identified. Some students experienced delays in loading the application, which may affect usability and learning efficiency. Additionally, certain worksheet items were perceived as difficult to understand, indicating the need for improvement in instructional clarity. Another limitation was students' limited familiarity with technology-based learning, which influenced their initial interaction with the media.

Despite these challenges, the overall findings indicate that the AR-based learning media effectively supports students' spatial ability, as evidenced by the high level of practicality and the proportion of students achieving the expected learning outcomes.

### Discussion

The findings of this study indicate that the developed augmented reality (AR)-based interactive learning media achieved a satisfactory level of validity, as reflected in expert validation scores. This result suggests that the instructional design, content structure, and technological integration are aligned with pedagogical standards and learning objectives. Conceptually, this supports the argument that well-designed digital learning environments can effectively bridge the gap between abstract mathematical concepts and concrete representations, particularly in geometry learning. From the perspective of instructional design theory, the integration of content accuracy and media

usability is essential in ensuring meaningful learning experiences (Mayer, 2024). The validation results are consistent with prior studies demonstrating that AR-based media can meet quality standards when developed through systematic frameworks (Arena et al., 2022; Tian & Ironsi, 2025). However, the moderate validity scores also indicate that the constructivist dimension of the media could be further enhanced, as suggested by expert feedback. This implies that while the media is structurally sound, deeper opportunities for knowledge construction and learner autonomy should be incorporated. Therefore, the validity findings not only confirm the feasibility of the product but also highlight areas for pedagogical refinement.

The practicality of the developed media, as indicated by high student response scores, reflects its usability and acceptance within a real classroom context. This finding implies that AR-based learning environments can enhance students' engagement and interaction with learning materials, which are critical components of effective instruction. From a theoretical standpoint, this aligns with the principles of student-centered learning and experiential learning theory, where active engagement and interaction foster deeper understanding (Bhardwaj, 2025). The high practicality scores are also consistent with recent studies emphasizing the role of AR in improving user experience and learning motivation (Wu et al., 2024; Li et al., 2025). Nevertheless, the presence of lower scores in certain aspects, such as loading time and question clarity, suggests that technological and instructional design constraints still influence user experience. These limitations highlight the importance of balancing technological sophistication with usability considerations. Consequently, the practicality findings extend existing research by demonstrating that AR effectiveness is not solely dependent on its visual features but also on its operational efficiency and instructional clarity.

Furthermore, the effectiveness of the media, evidenced by the high percentage of students achieving the Minimum Passing Score, indicates that AR-based learning can significantly support the development of spatial ability. This finding is particularly meaningful when interpreted through the lens of spatial cognition theory, which posits that the ability to manipulate and visualize three-dimensional objects is enhanced through interactive and visual experiences (Gardony et al., 2021). The use of AR enables learners to engage in dynamic manipulation of geometric objects, thereby strengthening mental rotation and spatial visualization skills. This result is consistent with previous research demonstrating the positive impact of AR on spatial reasoning and academic achievement (Supli & Yan, 2024; Özdemir & Özçakır, 2026). However, it is important to note that the effectiveness measure relies on descriptive thresholds rather than inferential statistical analysis, which may limit the strength of causal claims. Despite this limitation, the findings provide empirical support for the integration of immersive technologies in mathematics education. Thus, the effectiveness results reinforce the theoretical proposition that embodied and interactive learning environments enhance cognitive processing in geometry.

Another significant finding lies in the structured integration of spatial ability indicators within the AR-based learning design. The incorporation of spatial perception, visualization, mental rotation, spatial relations, and orientation into the instructional framework reflects a comprehensive approach to developing spatial cognition. This aligns with the multidimensional model of spatial ability proposed in educational psychology, which emphasizes the interrelated nature of these components (Nagy-Kondor, 2017; Porat & Ceobanu, 2023). Compared to previous studies that often focus on general spatial skills, this research explicitly embeds these indicators into both the learning activities and assessment design. This approach extends prior work by offering a more systematic alignment between instructional objectives and cognitive outcomes (Lowrie et al., 2019; Harris, 2023). However, the extent to which each indicator contributes differentially to learning outcomes remains unexplored. This suggests a need for more granular analysis in future studies. Therefore, this finding contributes conceptually by proposing a more structured and indicator-based approach to spatial ability development in AR environments.

The implementation process also reveals that contextual factors, such as students' familiarity with technology and classroom infrastructure, play a critical role in shaping learning outcomes. While the AR media was generally well-received, some students experienced initial difficulties due to limited exposure to technology-based learning tools. This finding supports the argument that technological integration in education is not merely a matter of tool availability but also of digital readiness and user competence (Zulfiqar et al., 2023). In contrast to studies conducted in technologically advanced settings, where AR adoption is more seamless, the current context highlights challenges related to accessibility and adaptation (Trisnawati et al., 2025). These contextual differences may explain variations in effectiveness across studies. Moreover, the time required to operate the media suggests that cognitive load considerations must be addressed in AR design. Thus, this study underscores the importance of contextualizing technological interventions within specific educational environments, rather than assuming universal applicability.

In addition, the findings suggest that AR-based learning fosters not only cognitive outcomes but also affective engagement, as reflected in increased student interest and participation. This dual impact aligns with the cognitive-affective theory of learning, which posits that emotional engagement enhances information processing and retention (Schneider et al., 2022). The interactive nature of AR allows students to explore content actively, thereby creating a more meaningful and enjoyable learning experience. Similar findings have been reported in recent studies highlighting the role of AR in improving student motivation and flow experience (Wu et al., 2024; Tarnq et al., 2024). However, it is also possible that the novelty effect of AR contributes to increased engagement, which may diminish over time. This raises questions about the sustainability of AR's motivational impact. Therefore, while the affective benefits of AR are evident, further longitudinal research is needed to examine their persistence.

Critically, the study contributes to the ongoing discourse on technology-enhanced learning by demonstrating that the effectiveness of AR is contingent upon its pedagogical integration rather than its technological sophistication alone. Unlike studies that treat AR as an isolated tool, this research embeds AR within a structured instructional design framework, thereby enhancing its educational value. This finding supports the argument that meaningful learning occurs when technology is aligned with clear learning objectives and cognitive processes (Li et al., 2025). At the same time, the reliance on descriptive evaluation methods highlights a methodological limitation that should be addressed in future research. More rigorous experimental designs and statistical analyses are needed to establish stronger causal relationships. Nevertheless, the study provides a valuable model for integrating AR with spatial ability development in mathematics education.

Finally, this research offers both theoretical and practical contributions by addressing gaps in the literature related to content specificity and systematic development of AR-based learning media. The focus on polyhedra, combined with the integration of spatial ability indicators and the ADDIE model, provides a novel framework that extends existing approaches. Theoretically, it enriches the understanding of how immersive technologies can support specific cognitive skills in mathematics learning. Practically, it offers educators a feasible and effective tool for enhancing geometry instruction. Compared to prior studies that emphasize general AR applications, this research provides a more targeted and structured approach. However, the limited sample size and context-specific implementation constrain the generalizability of the findings. Therefore, future research should explore broader applications and incorporate more diverse samples. Overall, this study positions itself within the global literature as a meaningful contribution to the advancement of technology-integrated mathematics education.

## CONCLUSION

This study demonstrates that the development of a 3D interactive learning medium based on Augmented Reality (AR) for Android applications, implemented through the ADDIE model, provides a systematically validated and pedagogically meaningful solution for enhancing students' spatial ability in learning polyhedra. The findings confirm that the developed media meets the criteria of validity, practicality, and effectiveness, as evidenced by expert validation results, positive student responses, and the high proportion of students achieving the Minimum Passing Score. More importantly, the integration of spatial ability indicators such as spatial perception, visualization, mental rotation, spatial relations, and spatial orientation into the design of the AR media contributes to a deeper conceptual understanding by bridging abstract geometric representations with concrete, interactive experiences. From a theoretical perspective, this study reinforces the role of technology-enhanced learning in supporting cognitive processes related to spatial reasoning, particularly through immersive and manipulable visual environments. Practically, the developed media offers an accessible and engaging instructional tool that aligns with the demands of 21st-century learning, promoting active participation, independent exploration, and meaningful learning experiences. Nevertheless, the study is limited by its relatively small sample size and specific implementation context, which may affect the generalizability of the findings. Therefore, future research is recommended to expand the scope of implementation, incorporate more rigorous experimental designs, and further explore the integration of AR technology across broader mathematical topics. Overall, this study contributes to the advancement of mathematics education by providing a validated framework for developing AR-based learning media that effectively supports students' spatial ability and conceptual understanding.

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## AUTHOR CONTRIBUTIONS STATEMENT

**ADU** was responsible for the research design, instrument development, data collection, data analysis, and the entire research process, including the drafting of the article. **FYAR** contributed to the development of an Augmented Reality-based 3D interactive learning medium using an Android application to support spatial skills and other instruments, and played a role in its implementation. **SAN** assisted in drafting the article, organizing the content, and revising the manuscript based on the team's feedback. Finally, **NA** contributed to field data collection and assisted in validating the learning media's practicality and effectiveness.

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