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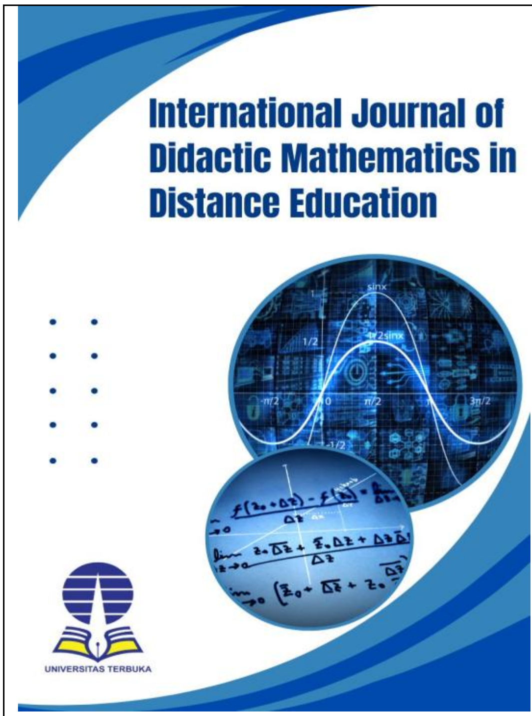

Integrating markerless augmented reality into project-based learning to foster spatial reasoning and self-regulated learning in junior high school: A formative evaluation

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Integrating markerless augmented reality into project-based learning to foster spatial reasoning and self-regulated learning in junior high school: A formative evaluation

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Abstract
Integrating markerless Augmented Reality (AR) into Project-Based Learning (PBL) through a structured worksheet offers a promising approach to support geometry learning at the junior high school level. This study reports a formative evaluation of a PBL-based worksheet integrated with explicit self-regulated learning (SRL) prompts and supported by a markerless AR application (AR Dreamhouse), designed to foster students' spatial reasoning in learning polyhedra. The study was conducted at a junior high school in Bandung, Indonesia, in August 2025. The formative evaluation involved six expert validators (content, media, and pedagogy) and nine ninth-grade students in a small-group trial. Data were collected using expert validation sheets and a student response questionnaire and analyzed using the Content Validity Index (CVI) and descriptive statistics. Expert validation showed perfect agreement across all aspects (S-CVI/Ave = 1.00), indicating high content, media, and pedagogical validity of the worksheet and AR application. Student responses were highly positive ($M = 3.64$ out of 4, $SD = 0.25$), with particularly strong agreement on collaboration, engagement, and clarity of learning activities. These results indicate that the AR-integrated PBL worksheet is feasible and well accepted by junior high school students. The study provides formative evidence that integrating markerless AR into worksheet-based PBL can create a consistent and engaging learning experience, and it offers practical implications for teachers and learning designers seeking to develop technology-supported geometry instruction in secondary education.

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1. Introduction

Spatial reasoning is widely recognized as a fundamental cognitive foundation in mathematics education, particularly in learning three-dimensional geometry, which requires students to visualize, represent, and mentally manipulate spatial objects that are not directly observable (Mulligan et al., 2020; NCTM, 2000). Numerous recent studies report that students experience persistent difficulties in interpreting three-dimensional representations, understanding spatial relationships, and connecting visual information with formal geometric concepts, especially when learning polyhedral topics such as prisms and pyramids (Kurt et al., 2023; Woolcott et al., 2020). These challenges indicate that success in geometry learning is not merely procedural but depends heavily on students' ability to reason spatially.

A more recent definition by the Spatial Reasoning Study Group (SRSG) characterizes spatial reasoning as the capacity to mentally recognize and manipulate the spatial properties of objects and their relationships (Bruce et al., 2017; Davis & Spatial reasoning Study Group, 2015). This ability involves constructing mental images, transforming spatial representations, and reasoning about objects in space, all of which are essential for understanding multidimensional geometric concepts (Linn & Petersen, 1985; Pahmi et al., 2024; Woolcott et al., 2020). Beyond mathematics classrooms, spatial reasoning plays a crucial role in various professional fields such as engineering, architecture, and medicine, as well as in everyday activities like navigation and interpreting visual information (Gagnier et al., 2022; Wai et al., 2009). Empirical evidence further shows that spatial reasoning is strongly associated with students' mathematical achievement and, in some cases, serves as a stronger predictor than verbal ability (Mix & Cheng, 2012). Despite its recognized importance, many students struggle to develop spatial reasoning because classroom instruction often provides limited opportunities for active visualization and manipulation of three-dimensional objects (Kurt et al., 2023), a challenge that has also been reported among prospective mathematics teachers (Patahuddin et al., 2022).

To address the persistent challenges in developing students' spatial reasoning in geometry learning, attention must be given not only to instructional content but also to students' learning processes. One important aspect of these processes is self-regulated learning (SRL), which refers to students' ability to plan, monitor, and evaluate their learning activities in pursuit of personal learning goals (Zimmerman, 2002). Previous studies have shown that SRL plays a critical role in academic success and is considered a core competence in 21st-century education (Cleary et al., 2021; Nurjanah et al., 2020). In the context of geometry learning, spatial reasoning tasks often require sustained attention, strategic exploration, and reflective evaluation, indicating a close conceptual relationship between spatial reasoning and SRL.

Efforts to foster both spatial reasoning and SRL must be aligned with the characteristics of today's learners, most of whom belong to Generation Z. Born between 1995 and 2015, Generation Z students have grown up in digitally rich environments and demonstrate strong preferences for visual, interactive, and technology-supported learning experiences (Cretu et al., 2020; DiMattio & Hudacek, 2020). They tend to value autonomy, collaboration, and engagement with real-world problems, which calls for instructional approaches that are flexible and student-centered (Manzoni et al., 2021; Szymkowiak et al., 2021). These characteristics demand a learning environment that integrates digital tools meaningfully rather than treating technology as an add-on.

Project-Based Learning (PBL) has been widely recognized as an instructional approach that supports active learning through authentic, inquiry-driven tasks and collaborative problem solving (Kokotsaki et al., 2016; Krajcik & Shin, 2014). When combined with Augmented Reality (AR), PBL offers additional affordances for visualizing and interacting with three-dimensional geometric objects in meaningful contexts (Ahmad & Junaini, 2020; Schutera et al., 2021). However, most previous studies in mathematics education have relied on marker-based AR, which requires printed markers and may limit flexibility and spontaneity in learning activities (Mandala et al., 2025; Nindiasari et al., 2024). In contrast, markerless AR utilizes computer vision to place virtual objects directly within real environments without physical markers, enabling more natural and immersive learning experiences that align well with PBL principles (Radu, 2014).

Although Project-Based Learning has been widely examined in school contexts (Kokotsaki et al., 2016), studies on augmented reality in mathematics education have predominantly relied on marker-based approaches and have rarely addressed self-regulated learning as an explicit learning objective (Ahmad & Junaini, 2020; Isharyadi & Herman, 2022). As a result, the integration of markerless augmented reality into Project-Based Learning to simultaneously support students' spatial reasoning and self-regulated learning remains limited, particularly at the junior high school level. Moreover, existing AR-based studies have tended to emphasize learning outcomes or technological effectiveness, with limited attention to the feasibility of integrated instructional designs prior to large-scale implementation. Therefore, this study aimed to develop and conduct a formative evaluation of a Project-Based Learning worksheet integrated with markerless augmented reality to support junior high school students' spatial reasoning and self-regulated learning. This study was guided by the following research questions: (1) How feasible is a Project-Based Learning worksheet integrated with markerless augmented reality in supporting students' spatial reasoning and self-regulated learning? and (2) How do students respond to the use of the markerless AR-integrated PBL worksheet in geometry learning?

2. Method

This study constitutes a developmental research focusing on the formative evaluation stage within the ADDIE instructional design model (Analysis, Design, Development, Implementation, and Evaluation) (Branch, 2009). The ADDIE model was employed to provide a systematic and structured framework for developing, testing, and refining instructional products prior to large-scale implementation, as it guides instructional design through iterative phases of design and evaluation (Senadheera et al., 2024; Spatioti et al., 2022). In this manuscript, the research specifically reports the formative evaluation phase, which is intended to identify design strengths, weaknesses, and areas requiring revision in order to examine the feasibility and initial quality of the developed learning product before proceeding to implementation and summative evaluation stages (Plomp, Nieveen & Folmer, 2013; Tessmer, 1993). The implementation and summative evaluation phases are planned to be conducted and reported in subsequent studies.

2.1 Product Description

The product evaluated in this study was a Project-Based Learning (PBL) student worksheet integrated with markerless Augmented Reality (AR), designed to support the development of students' spatial reasoning and self-regulated learning (SRL) in three-dimensional geometry topics, particularly polyhedra. Markerless AR was selected because it allows virtual objects to be placed directly within real environments without the need for printed markers, offering greater flexibility, ease of use, and immersive interaction compared to marker-based AR (Radu, 2014; Tiwari & Bhagat, 2024).

The AR application was developed for Android smartphones and designed to display three-dimensional house models corresponding to the project tasks presented in the student worksheet. The application enabled students to explore the 3D house model from multiple perspectives, allowing them to observe spatial structures in detail. Interactive features were provided to support project-based activities, including opening doors and modifying interior elements such as floors and walls according to the project requirements. The three-dimensional models were created using Blender, and the AR application was implemented using Vuforia. The developed AR system employed markerless AR technology, which required only a flat surface to display the virtual objects, allowing students to visualize and manipulate the 3D models without the use of printed markers.

2.2 Participants and Sampling

The participants consisted of six expert validators and nine ninth-grade students from a public junior high school in Bandung. Expert validators were selected purposively based on the following criteria: holding at least a master's degree in a relevant field, having a minimum of five years of experience in teaching or instructional media development, and/or possessing scholarly publications in mathematics education or educational technology. The panel included two mathematics content experts, two instructional media experts, and two pedagogical experts. The student participants involved in the small-group trial were selected using convenience sampling, based on accessibility and the availability of Android devices capable of running the AR application.

2.3 Research Procedure

Formative evaluation was conducted through two main activities: expert review and small-group trial, following Tessmer (1993) formative evaluation framework. During the expert review stage, validators assessed the feasibility of the instructional content, media functionality and appearance, and pedagogical alignment with PBL and SRL principles. Revisions were made based on quantitative scores and qualitative feedback prior to student testing.

The small-group trial involved nine students working in three groups of three. The activity was conducted in a regular classroom setting and lasted for approximately 50 minutes, consisting of an orientation session on using the AR application (10 minutes), completion of PBL-based worksheet activities integrated with AR (30 minutes), and a reflection session followed by completion of a student response questionnaire (10 minutes).

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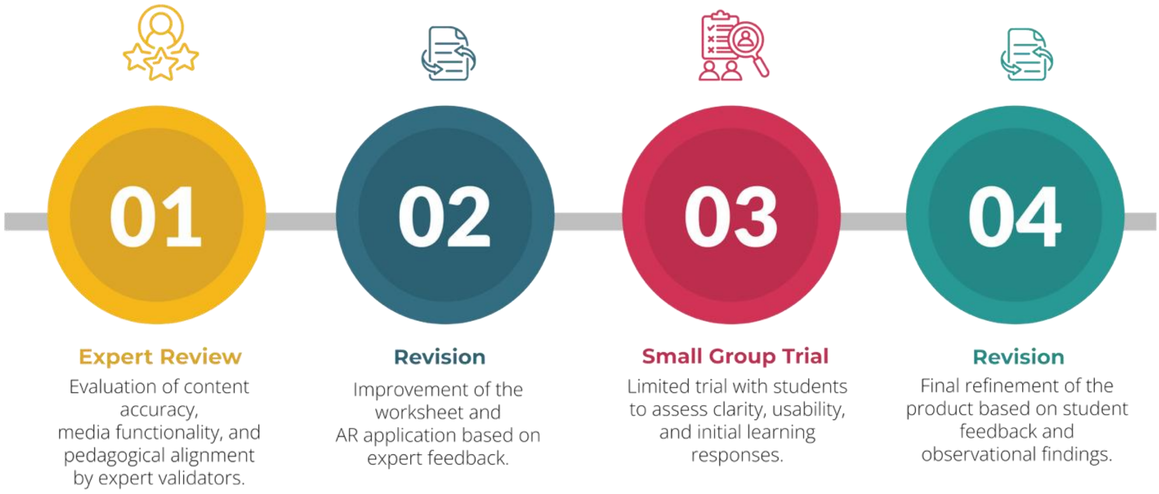
Figure 1
Procedural Steps of the Formative Evaluation



2.4 Instruments and Data Analysis

Two instruments were used for data collection: an expert validation sheet and a student response questionnaire. The expert validation sheet employed a four-point Likert scale (1 = not relevant, 4 = highly relevant) to evaluate content accuracy, media quality, and pedagogical suitability. This scale was adapted based on Content Validity Index (CVI) guidelines (Lynn, 1985), where ratings of 3 or 4 indicate item relevance. Quantitative data from expert validation were analyzed using the Content Validity Index (CVI). The Item-Level CVI (I-CVI) was calculated as the proportion of experts assigning a score of 3 or 4 to each item, while the Scale-Level CVI (S-CVI/Ave) was obtained by averaging all I-CVI values (Polit et al., 2007). The product was considered to demonstrate high content validity if all items achieved an I-CVI of 1.00 and the S-CVI/Ave was at least 0.90, indicating strong agreement among experts regarding item relevance.

The student response questionnaire consisted of eight closed-ended statements using a four-point Likert scale and one open-ended question, addressing students' engagement, ease of use, conceptual understanding, and perceived usefulness of the AR-integrated worksheet. Student response data were analyzed descriptively by calculating the mean score for each item and categorizing the results according to predefined rating criteria. Qualitative data from expert comments, observations, and open-ended responses were analyzed thematically to identify the product's strengths, weaknesses, and recommendations for improvement.

2.5 Ethical Considerations

Ethical considerations were addressed throughout the study. Permission to conduct the research was obtained from the school administration, and students voluntarily agreed to participate in the study. Students' identities were anonymized, and all data were used solely for research purposes in accordance with institutional ethical guidelines.

3. Results and Discussion

3.1 Results

To address the research questions, the results are organized into two parts: (1) expert validation results to examine the feasibility of the developed product (RQ1), and (2) student responses from the small-group trial to explore the practicality and initial user perceptions of the AR-integrated PBL worksheet (RQ2).

3.1.1 Feasibility of the AR-Integrated PBL Worksheet (RQ1)

The formative evaluation stage in this development research plays a strategic role in ensuring that the developed product meets feasibility standards before being implemented on a larger scale. This evaluation not only provides information related to content quality, media appearance, and pedagogical alignment, but also serves as an essential basis for assessing the media's readiness for use by students as end users. Therefore, this section presents the results of expert validation of the PBL-worksheet and the markerless AR application, as well as the findings from a small-scale trial involving junior high school students.

The product developed in this study consists of two integrated components: a project-based student worksheet and a markerless AR application. Both are designed to support geometry learning at the junior high school level, particularly on the topic of polyhedra (prisms and pyramids), while simultaneously fostering students' spatial reasoning and SRL. The worksheet is structured using a PBL approach, enabling students to engage in learning through a series of contextual and collaborative activities. It guides students to design their "dream house" project—starting from identifying spatial needs, sketching design plans, calculating surface area and volume, to estimating paint requirements as part of applied mathematics activities. Additionally, the worksheet includes reflection prompts and metacognitive tasks explicitly supporting key SRL components such as planning, monitoring, and self-evaluation. A sample page of the worksheet is shown in Figure 2.

Figure 2

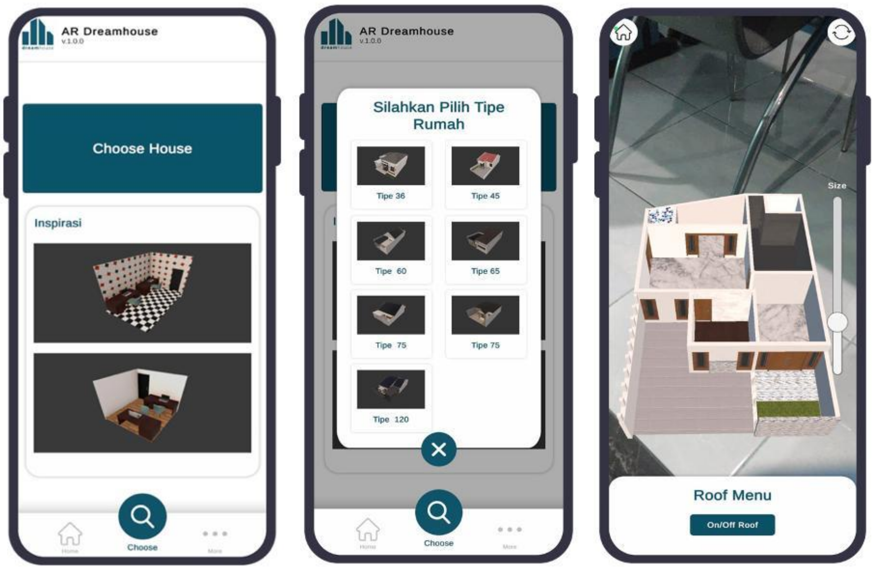
Example pages of the project-based student worksheet

To complement the visual and exploratory experience, a markerless AR application called AR Dreamhouse was also developed. This application allows students to display 3D models of houses directly onto real surfaces using a smartphone camera, without requiring any physical markers. With its interactive features, students can manipulate 3D objects, explore various viewing angles, and compare the geometric shapes they designed in the worksheet with more concrete digital visualizations. The application also includes a house catalog with various design types corresponding to different geometric forms and sizes, and a feature that enables users to open or close the roof virtually to examine the internal structure of the space. The user interface of the application is shown in the figure 3.

These two media components—the worksheet and the AR application—are designed to be integrated and complementary in the learning process. The worksheet acts as a guide for project-based activities, while the AR application enhances spatial representation and students' visual understanding of geometry concepts. Validation of both products was conducted by experts in terms of content, media design, and pedagogical alignment, and tested through a small-scale trial involving nine students as end users. This formative evaluation provides an initial overview of the product's feasibility, instructional design quality, and its potential impact on students' learning experiences in the digital age.

Figure 3.

AR Dreamhouse application interface: house selection and 3D object visualization



One of the main aspects validated was content quality, particularly the alignment with geometry competencies, integration of the PBL approach, and support for the development of SRL. The validation was conducted by two subject matter experts using a 4-point Likert scale and analyzed using the CVI method as proposed by Lynn (1985). The results showed that all items received high ratings from both validators (I-CVI = 1.00), indicating that no items were considered unfit. Overall, the Scale-CVI (S-CVI) also reached 1.00, indicating an exceptionally high level of content validity. A summary of the content validation results is presented in the following table.

Table 1

Summary of Content Validity for the Project-Based Learning Worksheet and AR Application (Material Aspect)

Evaluation Aspect	Number of Items	Average I-CVI	Validity Category
Alignment with Geometry Learning Objectives	7	1.00	Highly Valid
Integration of Project-Based Learning (PBL)	4	1.00	Highly Valid
Support for Self-Regulated Learning (SRL)	4	1.00	Highly Valid
Total / Overall (S-CVI)	15	1.00	Highly Valid

In addition to providing quantitative assessments of media feasibility, the media experts also offered qualitative feedback for further development. The first validator recommended that at the beginning of the material, students be facilitated in understanding the elements of three-dimensional shapes—such as vertices, edges, and faces—through real-life representations like house columns, floors, walls, and ceilings. This was considered essential to ensure students' comprehension of geometric solids remains holistic and contextual. Furthermore, the validator suggested adding a scenario in the "dream house design" project to emphasize that available land is not always rectangular or square. In this context, students could be encouraged to maximize the use of irregular plots, thereby opening opportunities to design spaces other than cubes or rectangular prisms, such as trapezoidal prism-shaped rooms. Regarding the cost estimation of painting, the validator advised that formulas should not be provided directly. Instead, students should be given stimuli to explore such information from their surroundings, such as parents, neighbors, or construction workers. These suggestions have been incorporated in the revised version of the media.

The second validator provided feedback on language use, emphasizing the importance of maintaining consistency in the use of address terms such as "kamu" (you/informal) or "Anda" (you/formal) throughout the worksheet. Additionally, the validator noted that while the topic of nets of prisms and pyramids is included in the junior high school curriculum, it was not explicitly addressed in the worksheet, although it was made available in the supporting module. These inputs have been essential in refining the media to ensure that the developed product is not only valid in terms of content, but also communicative, contextual, and aligned with the intended instructional goals.

Beyond content aspects, validation was also conducted on the visual and functional quality of the media, which included the interface of the Augmented Reality (AR) application and the visual design of the student worksheet. This validation aimed to ensure that the media was not only informative and content-relevant, but also visually appealing, user-friendly, and capable of supporting student engagement in the learning process. Two media experts were asked to assess 15 indicators related to visual appeal, readability, navigation ease, interactivity, and accessibility of the media. The evaluation used a 4-point Likert scale and the results were analyzed using the CVI approach. The following table presents a summary of the average scores for each media validation indicator.

Table 2
Summary of Content Validity for the Project-Based Learning Worksheet and AR Application (Media Aspect)

Evaluation Aspect	Number of Items	Average I-CVI	Validity Category
Visual Design and Realism	5	1.00	Highly Valid
Accessibility and Readability	3	1.00	Highly Valid
AR Navigation and Interactivity	4	1.00	Highly Valid
Support for Independent Learning	3	1.00	Highly Valid
Total / Overall (S-CVI)	15	1.00	Highly Valid

In addition to providing quantitative assessments through the rating scale, the validators also offered valuable qualitative feedback for the further development of the learning media. The first validator noted that, overall, the visual design of the application was proportional and realistic; however, it was recommended to enhance the resolution in certain viewing angles to avoid blurriness when zoomed in or viewed at close range. Although the object manipulation feature was functioning properly, the rotation response was found to be somewhat sluggish on lower-specification devices, prompting a recommendation for further optimization. The 3D geometric visualizations in the application were considered supportive of spatial learning, yet the validator suggested adding a real-time comparison feature between two-dimensional (2D) and three-dimensional (3D) forms. Unfortunately, this could not be implemented due to technical limitations. Regarding compatibility, the application performed well on most newer Android devices, but it was still advised to conduct additional testing on lower-end devices to ensure inclusivity. Lastly, while the usage instructions in the worksheet were deemed sufficiently clear, the validator recommended adding a visual guide or brief video tutorial to assist students who may be less familiar with AR technology—this feedback has been addressed in the revised version of the media.

Table 3
Summary of Content Validity for the Project-Based Learning Worksheet and AR Application (Pedagogical Aspect)

Evaluation Aspect	Number of Items	Average I-CVI	Validity Category
Active and Collaborative Learning	4	1.00	Highly Valid
Student Autonomy and Self-Regulation	5	1.00	Highly Valid
Alignment with PBL Principles and Teacher Facilitation	6	1.00	Highly Valid
Total / Overall (S-CVI)	15	1.00	Highly Valid

In addition to quantitative assessments, the pedagogical experts provided essential qualitative feedback to refine the instructional design. The first validator suggested that the house catalog in the media should be arranged systematically based on size, from the smallest to the largest (e.g., types 45, 60, 65, 75, and 120), and complemented with both two-dimensional floor plans and three-dimensional visualizations. This arrangement aims to facilitate students' understanding of spatial structure and the interrelationships among geometric elements.

The second validator highlighted several technical and substantive aspects of the worksheet. They recommended separating the columns for "function" and "reason" on a specific page to make the information more structured and suggested introducing a relevant contextual problem before students are asked to calculate the surface area of the roof. Furthermore, the validator emphasized the importance of incorporating contextual problems related to pyramid shapes to ensure this geometric form is not overlooked in the house design exploration process. The explicit reinforcement of Project-Based Learning characteristics within the worksheet was also stressed as a critical element to be included. All of this feedback has been incorporated into the media revision and refinement process prior to its implementation in the small-scale trial phase.

3.1.2 Student Responses to the AR-Integrated PBL Worksheet (RQ2)

The limited-scale trial involved nine 9th-grade students to assess the practicality and initial impact of the developed Project-Based Learning worksheet integrated with markerless Augmented Reality (AR). The evaluation focused on students' perceptions regarding clarity of instruction, ease of use, learning motivation, and collaborative experience. Based on the student questionnaire consisting of eight statements, the average score obtained was 3.64 out of 4, indicating a very good level of acceptance. Table below summarizes the average student response for each statement:

Table 4

Student Response Summary on the Practicality of the PBL Worksheet and AR Application

Statement	Average
I understood the steps I had to take in the worksheet.	3.89
I was able to use the AR application without significant difficulties.	3.11
This activity made me more interested in learning geometry.	3.67
The worksheet helped me understand what I had to do.	3.78
I was able to collaborate with my group members during this activity.	4.00
I want to try more learning activities using AR like this.	3.56
I felt this activity was enjoyable and different from usual learning.	3.67
Some parts of this activity were confusing for me.	3.44

The highest score (4.00) was found in students' perception of collaboration, showing strong engagement and group work. Meanwhile, the lowest score (3.11) was related to difficulties in using the AR app on some devices, indicating an area for technical refinement. In addition to the quantitative data, students shared enthusiastic comments in the open-ended section. Many expressed that learning with AR was engaging, visual, and enjoyable. They appreciated the collaborative nature of the activity and noted that it changed their perspective on learning mathematics. One student stated, "I realized that learning math can actually be fun, especially with tools like AR." Another mentioned, "This method should be used more so that students who struggle with math can learn in a more interactive way." These responses reflect a strong positive reception and demonstrate the potential of AR-integrated PBL to enhance spatial reasoning and motivation.

3.2 Discussion

The results of formative evaluation in this study indicate that the worksheet based on PBL and the markerless AR application developed have met the eligibility criteria in terms of content, media, and pedagogy. The high content validity, as evidenced by I-CVI and S-CVI scores reaching 1.00, indicates that the learning media have been consistently designed with the objectives of geometry learning in mind, and support the development of spatial reasoning and SRL. This study originates from the empirical challenge that students—even prospective teachers—often struggle to visualize and manipulate spatial objects, particularly in the topic of three-dimensional geometry (Kurt et al., 2023; Patahuddin et al., 2022). Findings from the small-scale trial support this premise, where the AR application plays a significant role in bridging the gap between abstract representations and concrete visualizations of 3D shapes. This aligns with findings by Ahmad and Junaini, 2020 as well as (Schutera et al., 2021), which demonstrate that the use of AR in geometry learning can enhance student engagement and spatial representation skills. Previous developmental research has also explored the integration of Project-Based Learning and augmented reality in geometry contexts and reported positive support for students' visual-spatial understanding (Lainufar et al., 2021). However, these studies mainly focused on learning outcomes or media use, rather than examining the formative feasibility of an integrated instructional design prior to large-scale implementation.

The integration of SRL strategies into the student worksheet contributes meaningfully to more independent and reflective learning. The explicit inclusion of planning, monitoring, and self-evaluation components encourages students to autonomously manage their learning progress and project completion strategies. This is supported by pedagogical expert validation and student responses indicating active engagement and understanding of the learning process. These findings are consistent with (Cleary et al., 2021), who emphasize that metacognitive skills enable students to recognize their strengths and weaknesses and adjust their learning strategies to improve academic effectiveness. Furthermore, the PBL approach employed also fosters a culture of independent learning, where the responsibility for learning shifts from the teacher to the students through active involvement in project design and decision-making (Kokotsaki et al., 2016). In this study, spatial reasoning and self-regulated learning are positioned as parallel learning objectives that are jointly supported through the instructional design, rather than treating SRL as a separate or auxiliary component.

The main innovation of the developed product lies in the integration of markerless AR technology into instructional materials designed to support project-based learning, enabling students to visualize and manipulate three-dimensional objects within their physical surroundings without the use of physical markers (Buchner et al., 2021). Unlike the marker-based AR approach, this technology utilizes advanced computer vision algorithms to detect and enhance representations of the physical environment without relying on specific visual cues. It should be noted that the contribution of this study does not lie in demonstrating the effectiveness of markerless AR, but in examining its feasibility when integrated into a Project-Based Learning design through formative evaluation. These characteristics offer greater flexibility in creating spontaneous, immersive, and contextual learning experiences.

Several studies have shown that markerless AR has the potential to increase student engagement and enhance the sense of authenticity in the learning process, thereby supporting the creation of a more dynamic and responsive learning ecosystem (Tiwari & Bhagat, 2024). In the context of developing spatial reasoning, the interactive features offered by AR allow students to manipulate geometric objects contextually, aligned with the needs and scenarios of the projects they are working on. Moreover, this approach is also relevant to the learning characteristics of Generation Z, who exhibit a strong preference for visual, interactive, and technology-based learning (Cretu et al., 2020; Manzoni et al., 2021).

The readiness of the media for broader implementation is reflected in the fulfillment of content, media display, and pedagogical feasibility aspects, which have been thoroughly validated by experts. The validation results show that all indicators received high scores, indicating that the worksheet and the AR application developed meet the criteria as innovative and feasible learning media for geometry instruction (Plomp et al., 2013). In addition, positive responses from students during the small-scale trial suggest that the media were well-understood and succeeded in increasing students' interest and active engagement in the learning process. These findings indicate that the developed product is ready to be tested further in more diverse classroom contexts, involving a broader range of students and more comprehensive learning durations.

Feedback from validators and observational data indicate that several technical challenges remain, particularly limited visual resolution on lower-end devices and reduced responsiveness during object rotation. Although these issues did not significantly disrupt the learning process, they highlight the need for further technical refinement. In addition, the application requires Android devices with a minimum of 8 GB RAM and models released from 2020 onward, which may limit its implementation in schools with limited technological resources. Therefore, the findings of this formative evaluation should be interpreted as preliminary evidence of design feasibility, providing a basis for further large-scale implementation and studies that examine learning effectiveness. At the same time, this study contributes to the development of AR-integrated Project-Based Learning by illustrating how markerless AR and self-regulated learning strategies can be combined and evaluated at the formative stage, and by opening opportunities for future research on long-term learning outcomes and classroom integration.

Limitations

This study was conducted within the scope of formative evaluation; therefore, the findings provide initial insights into the feasibility and usability of the developed PBL-AR learning design rather than evidence of instructional effectiveness. The small-group trial was implemented within a limited instructional session, which did not allow for the examination of sustained classroom implementation or long-term impacts on students' spatial reasoning and self-regulated learning. In addition, variations in device performance were observed during the use of the markerless AR application, reflecting common constraints in mobile-based learning environments. These limitations indicate the need for future research involving larger and more diverse samples, longer intervention periods, and varied school contexts to examine learning outcomes more comprehensively. Further studies may also explore optimization strategies for broader device compatibility and investigate the effectiveness of the design through experimental or quasi-experimental approaches.

4. Conclusion

This study shows that the integration of Project-Based Learning and markerless Augmented Reality in geometry learning is feasible and practically applicable for supporting students' spatial reasoning and self-regulated learning at the junior high school level. The results of expert validation demonstrate a high degree of content accuracy, media quality, and pedagogical alignment, indicating that the developed worksheet and AR application meet essential instructional design standards. In addition, findings from the limited-scale trial reveal positive student responses related to instructional clarity, engagement, collaboration, and interactivity, suggesting that the learning design is well received and usable in classroom settings.

Rather than demonstrating instructional effectiveness, this study provides formative evidence that a PBL worksheet integrated with markerless AR can be systematically designed and refined to support geometry learning, particularly in three-dimensional topics. The use of contextual project tasks and interactive 3D visualization enabled students to engage more actively with geometric concepts and collaborate meaningfully during learning activities. These findings directly address the feasibility and initial user response aspects that guided the present study.

Based on these results, the developed learning design may serve as a reference for teachers and instructional developers who wish to integrate AR-supported Project-Based Learning into mathematics classrooms, especially to enhance students' visualization and engagement in geometry topics. Teachers are encouraged to consider device readiness, classroom management strategies, and project scaffolding when adopting this model. Future research is recommended to implement the learning design in larger and more diverse classroom contexts, to examine its long-term impact on students' spatial reasoning and self-regulated learning, and to evaluate learning effectiveness using experimental or quasi-experimental designs. Further development may also explore additional AR features and broader device compatibility to improve scalability and accessibility.

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Author Contribution

Author 1: Writing - original draft, Conceptualization, Formal analysis, Investigation, Methodology, Visualization;
Author 2: Supervision, Conceptualization, Writing – review & editing, Validation;
Author 3: Supervision, Methodology, Writing – review & editing;

Author 4: Supervision, 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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