Jurnal Pendidikan Matematika
UNIVERSITAS ISLAM MALANG

ARTICLE INFORMATION

Designing augmented reality to support spatial visualization in solid geometry: A needs-driven development approach

Muhamad Rifky Permadi, Satya Santika, Yeni Heryani, & Teerapat Piyaket
Corresponding author: satyasantika@unsil.ac.id

How to cite (APA Style):

Permadi, M. R., Santika, S., Heryani, Y., & Piyaket, T. (2026). Designing augmented reality to support spatial visualization in solid geometry: A needs-driven development approach. *Jurnal Pendidikan Matematika (JPM),* 12(2), 216–230. https://doi.org/10.33474/jpm.v12i2.25706

DOI	https://doi.org/10.33474/jpm.v12i2.25706
Contributions	**Muhamad Rifky Permadi**: CCP, MTD, SOF, INV, DAC, ANL, WOD, WRE. **Satya Santika**: SPV, VAL, WRE. **Yeni Heryani**: SPV, VAL, WRE. **Teerapat Piyaket**: WRE.
Funding	This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.
Conflict of Interest	The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.
Copyright ©	2026 Muhamad Rifky Permadi, Satya Santika, Yeni Heryani, and Teerapat Piyaket.
Declaration of AI Use	The authors declare that generative artificial intelligence (AI) tools were used solely to assist with language editing, grammar checking, clarity, and/or organization of the manuscript. AI tools were not used to generate research data, conduct statistical analyses, formulate research findings, or make scientific conclusions. The authors take full responsibility for the accuracy, originality, integrity, and final content of the manuscript and have reviewed and verified all AI-assisted content.

*** CRediT roles:** CCP: Conceptualization; MTD: Methodology; INV: Investigation; SOF: Software; DAC: Data Curation; ANL: Formal Analysis; WOD: Writing - Original Draft; WRE: Writing - Review & Editing; SPV: Supervision.

JURNAL PENDIDIKAN MATEMATIKA (JPM)
Vol. 12, No. 2, 2026, pp 216–230 e-ISSN: 2656–4564
https://doi.org/10.33474/jpm.v12i2.25706
online at: https://riset.unisma.ac.id/index.php/jpm/article/view/25706/

Designing augmented reality to support spatial visualization in solid geometry: A needs-driven development approach

Muhammad Rifky Permadi[1], Satya Santika[1*], Yeni Heryani, Teerapat Piyaket[2]
[1]*Universitas Siliwangi, Indonesia*
[2]*Yala Rajabhat University, Thailand*
Email: *satyasantika@unsil.ac.id*

ABSTRACT

This study developed and evaluated a Unity-based Augmented Reality (AR) learning medium designed to support eighth-grade students' spatial visualization in flat-sided solid geometry (cubes, cuboids, prisms, and pyramids). Using a Research and Development (R&D) approach structured by the ADDIE (Analysis, Design, Development, Implementation, and Evaluation) model. The media was built with Unity, Blender, Canva, and Vuforia. The distinctive feature is an interactive net-representation function that lets learners watch a solid unfold into its net and fold back, externalizing the net-to-solid transition that needs analysis identified as students' central difficulty. The product was validated by two material experts, two media experts, and two practitioner-teachers, and trialed with 12 students (small group) and 34 students (field). Validation placed the media in the "very feasible" category (material experts 96% and 91%; media experts 100% and 94%; practitioners 92% and 97%), and student responses in both trials were consistently positive for usability and practicality. Because the study assessed feasibility and practicality rather than learning outcomes, it does not claim measured gains in achievement or spatial visualization. Instead, it establishes a validated, classroom-ready medium whose effectiveness should be tested experimentally in future work.

Keywords: Augmented Reality, Spatial Visualization, Flat-Sided Solid Geometry, ADDIE, Unity, Mathematics Education.

*** Corresponding Author Email:** satyasantika@unsil.ac.id

Submission	Revised	Accepted	Published
July 5, 2026	August 10, 2026	August 17, 2026	August 29, 2026

How to cite (in APA style):
Permadi, M. R., Santika, S., Heryani , Y., & Piyaket, T. (2026). Designing augmented reality to support spatial visualization in solid geometry: A needs-driven development approach. *Jurnal Pendidikan Matematika (JPM)*, *12*(2), 216–230. https://doi.org/10.33474/jpm.v12i2.25706

INTRODUCTION

Mathematics underpins the growth of reasoning, problem solving, and spatial thinking, and geometry is one of the school subjects where these capacities are most visibly exercised. Within geometry, flat-sided solid figures (cubes, cuboids, prisms, and pyramids) occupy a central place in the junior secondary curriculum. Mastering them requires more than arithmetic fluency: students must coordinate the relationships among vertices, edges, and faces, reason about surface area and volume, and, crucially, hold and manipulate a three-dimensional image in mind. Success with this material depends as much on spatial visualization as on calculation, since learners must interpret two-dimensional drawings as genuine spatial objects (Kifthiyyah et al, 2024).

Spatial visualization deserves particular emphasis here because it is the cognitive engine driving most reasoning about solids. It covers the capacity to generate, retain, retrieve, and transform mental images of objects: mentally rotating a prism, decomposing a cuboid into familiar parts, or anticipating how a face will move when a net is folded. For flat-sided solids, this ability is not a peripheral skill but the gateway to understanding. A learner who cannot picture how the square faces of a cube meet at its edges will struggle to reason about its surface area, however fluently they manipulate the relevant formula. Because spatial visualization can itself be trained, it is a legitimate instructional target, and recent work shows that AR- and VR-based tools can be designed specifically to strengthen it (Ozcakir & Cakiroglu, 2021; Papakostas et al., 2022; Wong et al., 2021).

In practice, though, flat-sided solid geometry continues to be a stumbling block. A consistent theme across recent classroom studies is that weak spatial visualization, together with difficulty translating between two-dimensional and three-dimensional representations, leaves students unsure of what a figure actually looks like. The transition from a printed net to the assembled solid is especially troublesome: learners can recite the parts of a cube yet fail to imagine how its net folds into shape. Such gaps frequently harden into misconceptions that obstruct later understanding (Hrp et al., 2025; Ma'rufi & Alam, 2025). These observations point to a clear instructional need: media that make the invisible visible and let students rehearse the folding and rotating that ordinary textbooks cannot show.

The expansion of digital technology has given teachers new ways to meet that need. Instructional media matter precisely because they re-cast abstract ideas as concrete, manipulable representations, and a growing body of work argues that interactive digital resources heighten cognitive engagement and enrich the learning experience through visual and immersive displays (Hafizah, 2023). The benefit is particularly sharp in mathematics, where many objects of study cannot be handled physically. Technology supplies a stand-in that students can observe, question, and explore in ways conventional teaching rarely allows.

Introducing technology does not automatically improve learning. The benefit depends on how well a tool is matched to the cognitive demands of the content. Media that merely digitise a textbook page add little, whereas media that let students do something previously impossible, such as turning a solid in their hands, watching a net fold, or comparing cross-sections, can reshape how a concept is understood (Rodriguez-Saavedra et al., 2025). This distinction frames the present work: the aim was not to add technology for its own sake but to target a specific, well-documented difficulty with an affordance that conventional media cannot provide. The design question, accordingly, was less "how do we show solids?" than "how do we let students act on solids?"

Among emerging technologies, Augmented Reality (AR) has drawn sustained attention from educators. AR overlays virtual objects onto the physical environment and lets users interact with that digital content in real time, blending real and virtual elements into a single, meaningful visual experience that scaffolds the understanding of abstract concepts (Uriarte-Portillo et al., 2023). Empirical reports indicate that AR-rich settings lift engagement, motivation, and conceptual understanding in geometry (Nadzeri et al., 2024; Nindiasari et al., 2024), and broad reviews spanning twenty-five years of research and multiple education levels reach similar conclusions about AR's positive influence on learning (Avila-Garzon et al., 2021; Eryigit et al., 2025; Voulgari et al., 2024; Yu et al., 2022). Meta-analyses report medium-to-large effects of AR on mathematics and STEM achievement, thinking skills, and motivation (Flavin et al., 2025; Li et al., 2025), with the most recent syntheses confirming large gains in STEM courses (Hidayat et al., 2026).

A related strand explains why AR helps. By distributing information across the real and virtual fields and allowing multi-angle inspection, AR can ease the cognitive load of imagining three-dimensional structure (Ahmad & Siller, 2024). Systematic reviews caution that poorly designed AR can also raise load, so design principles drawn from multimedia learning matter (Buchner et al., 2022; Ceken & Taşkın, 2025; Elford et al., 2022). Immersive geometry environments built on the same logic have likewise improved motivation and performance (Su et al., 2022).

Despite this encouraging evidence, the existing literature leaves important gaps. These strands of work remain largely disconnected: studies tend either to measure learning outcomes or to appraise an application's technical performance, and rarely to trace how a documented learning difficulty drives specific design decisions. Herman et al. (2023), for instance, foregrounded gains in achievement, whereas Nazarudin et al. (2024) attended chiefly to application performance and system integration. Adoption-focused studies, in turn, model teachers' intentions to use AR rather than the design of the artefact itself (Ateş & Garzón, 2023). A large share of AR resources presents only static three-dimensional models and do little to depict the dynamic transformation of a net into a solid, the very process learners find hardest. Even existing Unity-based and marker-based AR applications for geometry typically stop at displaying rotatable solids. They seldom externalise the net-to-solid folding process itself, and they are rarely engineered backwards from an explicit, documented needs analysis. It is this specific shortfall, not the absence of AR geometry apps in general, that the present study addresses.

This study responds to that gap by developing a Unity-based AR learning medium for flat-sided solid geometry. Unity was chosen for its strength in building interactive three-dimensional environments and its smooth support for AR deployment on Android devices (Hussain et al., 2020). The novelty of the work is therefore not the use of AR as such, but the combination of three features rarely found together in prior media: a single application that unifies all four flat-sided solids; a dynamic net-representation function that animates the net-to-solid transition students find hardest; and a design whose every feature is traceable to a documented classroom need through a disciplined ADDIE process. To keep the product aligned with real classroom needs and instructional aims, its construction follows the ADDIE model throughout.

The choice of a Unity and Vuforia marker-based pipeline also warrant brief justification, since the platform shapes what the medium can do pedagogically. Marker-based AR anchors a virtual solid to a printed image target, so that a student who tilts or moves the card sees the figure respond as if it were physically present on the desk. This tight coupling between hand movement and visual feedback is pedagogically valuable: it lets learners adopt an exploratory, embodied stance toward a solid rather than passively viewing a fixed picture. Unity supplies the real-time rendering and interaction layer needed for such manipulation and exports readily to the Android devices common in Indonesian classrooms, while Blender, Canva, and Vuforia handle modelling, visual assets, and target recognition, respectively. The combination keeps the application lightweight enough for ordinary school hardware without sacrificing interactivity.

Accordingly, the study pursues four objectives: to identify the needs of students and teachers regarding AR learning media; to describe how the medium is developed in Unity; to evaluate the feasibility of the product through expert validation; and to examine students' responses to its use. Consistent with this feasibility-and-practicality scope, the study does not test learning effectiveness experimentally. Claims are confined to what the R&D design can support. The results are expected to advance the design of innovative mathematics media and to give teachers practical support for geometry instruction at the secondary level.

METHOD

This study used a Research and Development (R&D) approach to produce an Augmented Reality learning medium, built in Unity, for flat-sided solid geometry. The overarching aim was a valid and practical product designed to support students' spatial visualization and conceptual understanding. Following the four objectives above, the work sought to identify teachers' and students' needs for AR learning media, to construct the medium in Unity, to establish the product's validity through expert review, and to investigate students' responses once the product was implemented.

The development procedure adopted the ADDIE instructional-design model as adapted from Lee & Owens (2004), comprising five stages: Analysis, Design, Development, Implementation, and Evaluation. ADDIE was selected because it offers a systematic yet flexible scaffold for building technology-based educational products, with evaluation and revision woven through every stage rather than reserved for the end. The Analysis stage combined a needs assessment with a front-end analysis that examined the audience, the available technology, the learning tasks, the candidate media, and existing (extant) data. The decision to foreground spatial visualization as a design driver follows prior AR/VR training studies that treated spatial ability as an explicit, trainable design target (Ozcakir & Cakiroglu, 2021; Papakostas et al., 2022; Wong et al., 2021).

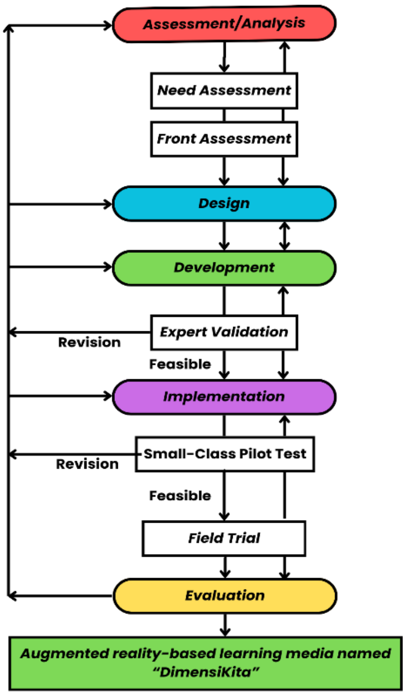

Figure 1. Research Procedure Based on the ADDIE Model

The front-end analysis that opened the project was deliberately multi-faceted. Audience analysis profiled the eighth-grade learners: their prior exposure to geometry, their familiarity with smartphones, and the specific points at which they lost track of a solid's structure. Technology analysis checked whether students could access Android devices capable of running an AR application and whether classroom conditions suited marker-based use. Task analysis broke the competencies expected for flat-sided solids into observable sub-tasks, from identifying faces and edges to reconstructing a solid from its net. Media analysis weighed candidate formats against these tasks and confirmed that interactive three-dimensional visualization offered advantages no static medium could match. A final extant-data analysis reviewed existing textbooks and digital resources to establish what was already available and where they fell short. These strands jointly defined the design requirements carried into the next stage.

The research took place at Public Junior High School (SMP Negeri) 10 Tasikmalaya, West Java, Indonesia. Participants comprised mathematics teachers, media experts, material experts, and eighth-grade students. Product trials proceeded in two phases: a small-group trial with 12 students and a field trial with 34 students. The two-step trial allowed early usability problems to be detected and corrected with a small sample before the medium was exposed to a larger, more representative group. Validators were selected purposively for relevant expertise: material experts assessed content correctness and curricular fit, media experts judged interface design and technical robustness, and the two participating teachers appraised classroom practicality from a practitioner's standpoint.

Data were gathered through interviews, questionnaires, validation sheets, and documentation. Semi-structured interviews with mathematics teachers surfaced instructional problems, students' learning difficulties, and the state of available technological facilities. Questionnaires were administered at two points: a needs-analysis questionnaire during Analysis captured students' characteristics, technological readiness, and learning difficulties, while a response questionnaire during Implementation measured usability and practicality. Validation sheets enabled media and material experts to judge the feasibility of the product, and documentation recorded the development activities throughout.

The validation instruments were developed from established educational-media indicators. The material-expert sheet covered content accuracy, curricular alignment, completeness, and instructional relevance. The media-expert sheet covered readability, intersheet covered readability, interface design, usability, program management, and documentation; and the practitioner sheet covered classroom practicality and learning support. Content validity of each instrument was established through expert judgement before data collection, with items revised for clarity in response to reviewers' comments. Internal consistency of the response questionnaires was checked, and the item structure was refined accordingly before the field trial. Full instrument blueprints (aspects and item counts) are summarised in Table 1.

Table 1. Research Instruments

Instrument	Data Source	Purpose	Instrument
Interview guide	Mathematics teachers	Identify instructional problems and needs	Interview guide
Need-analysis questionnaire	Eighth-grade students	Identify characteristics, technology readiness, difficulties	Need-analysis questionnaire
Validation sheet	Material & media experts	Evaluate feasibility of the product	Validation sheet
Response questionnaire	Students	Measure usability and practicality	Response questionnaire
Documentation sheet	Development activities	Record the development process	Documentation sheet

Each ADDIE stage carried distinct tasks. During Analysis, the researcher conducted the needs assessment and front-end analysis described above. During Design, the team prepared flowcharts, storyboards, and the research instruments, mapping the sequence of screens and the learning flow before any asset was built. The Development stage produced the three-dimensional geometric models and integrated them into an AR application in Unity, after which the prototype was submitted to media and material experts for validation and subsequent revision. Implementation comprised the small-group trial (12 students) followed by the field trial (34 students). Evaluation operated in two modes: formative evaluation accompanied every stage, while summative evaluation followed implementation.

Both qualitative and quantitative techniques were used to analyse the data. Qualitative material from interviews, observation, and documentation was interpreted descriptively to characterise needs and refine the product. Quantitative material from validation sheets and response questionnaires was summarised with descriptive statistics. All instruments used a five-point Likert scale from 1 (very poor) to 5 (very good), and the resulting totals were converted to percentages with Equation (1):

$$P = (f / N) \times 100\%$$

Where P is the percentage score, f is the total score obtained, and N is the maximum possible score. For the qualitative strand, interview transcripts and observation notes were read repeatedly, grouped into recurring themes(learning difficulties, technological readiness, and instructional needs), and used to inform design decisions and successive revisions of the prototype. A product was retained or revised based on both data strands: a low score on any validation aspect triggered targeted revision before the next stage, while expert comments guided the specific changes. The percentages were then interpreted against the feasibility and practicality criteria adapted from Riduwan (2022), as summarised in Table 2. A mean score in the 81–100% band marks the product as very feasible or very practical and signals readiness for the next stage of testing.

Table 2. Feasibility and Practicality Criteria

Percentage (%)	Category
81 – 100	Very feasible / Very practical
61 – 80	Feasible / Practical
41 – 60	Fairly feasible / Fairly practical
21 – 40	Less feasible / Less practical
0 – 20	Not feasible / Not practical

RESULT

Analysis

The Analysis stage drew on interviews with mathematics teachers and questionnaires completed by students at Public Junior High School (SMP Negeri) 10 Tasikmalaya. Two findings stood out. First, students reported genuine difficulty with flat-sided solid geometry, especially in picturing three-dimensional objects and connecting geometric ideas to concrete representations. Second, instruction still leaned heavily on conventional media, which gave learners few chances to explore solids interactively. Teachers added that the aids at hand (printed nets, wooden models, and board drawings) could not be manipulated by every student at once and could not show the folding process in motion. Students most often located their difficulty at the moment of moving between a net and the assembled solid, and between a drawing on paper and the object it depicted. This convergence between teacher and student accounts sharpened the design brief: the medium had to make geometric transformation visible and place that visualization in each learner's own hands.

Design and Development

Guided by the identified needs, the team developed an AR learning medium using Unity, Blender, Canva, and Vuforia. Blender was used to model the solids, Canva to design supporting visual assets, Vuforia to handle marker recognition, and Unity to assemble and deploy the interactive application. The finished medium offers several core features: learning materials, AR visualization, concept-understanding questions, practice exercises, summaries, usage instructions, and information pages. Its central feature lets students render cubes, cuboids, prisms, and pyramids as interactive three-dimensional objects that can be rotated, enlarged, reduced, and unfolded into net form, directly addressing the net-to-solid transition that the Analysis stage flagged as a key difficulty.

Each feature was designed to play a defined pedagogical role. The learning materials page presents definitions and properties of the four solids in a structured sequence. The AR visualization feature is the heart of the application, projecting a manipulable solid onto the image target. The concept-understanding questions prompt students to verbalise what they observe, linking the visual experience to formal vocabulary. The practice exercises consolidate procedural skills such as computing surface area and volume, and the summary, usage instructions, and information pages provide scaffolding, orientation, and provenance. Crucially, the net-representation function lets a student watch a solid open into its net and fold back again, making the two-dimensional to three-dimensional transition, identified in analysis as the principal difficulty, directly observable rather than merely described.

The product did not reach this form in a single pass. It evolved across the ADDIE cycle in response to expert feedback. Several weaknesses surfaced during development and validation. Material experts noted that early content lacked worked examples for prism and pyramid surface area and that some definitions were imprecise, so these were rewritten and expanded. Media experts identified unstable marker recognition under low light, inconsistent button placement across pages, and text that was hard to read on smaller screens; the team enlarged the image targets, standardised the navigation bar, and increased font contrast. Practitioner-teachers recommended clearer on-screen usage instructions for first-time users, which were added as a dedicated help page. Table 3 summarises the principal revisions from expert input; before-and-after screenshots of the interface and net-folding sequence are provided in Figures 2–3.

The product did not reach this form in a single pass; it evolved across the ADDIE cycle in response to expert feedback, and several weaknesses surfaced during development and validation. Material experts noted that early content lacked worked examples for prism and pyramid surface area and that some definitions were imprecise; these were rewritten and expanded. Media experts identified unstable marker recognition under low light, inconsistent button placement across pages, and text that was hard to read on smaller screens. In response, the team enlarged the image targets, standardised the navigation bar, and increased font contrast. Practitioner-teachers recommended clearer on-screen usage instructions for first-time users, which were added as a dedicated help page. Table 3 summarises the principal revisions from expert input. Before-and-after screenshots of the interface and net-folding sequence are provided in Figures 2 and 3.

Table 3. Summary of Expert Feedback and Corresponding Revisions

Aspect flagged	Expert/source	Revision made
Missing worked examples; imprecise definitions	Material experts	Added worked examples; rewrote definitions
Unstable marker recognition (low light)	Media experts	Enlarged/optimised image targets
Inconsistent navigation; low text contrast	Media experts	Standardised navigation; increased contrast/font size
Unclear first-use guidance	Practitioner-teachers	Added dedicated usage-instructions page

Figure 2. Main Interface of the Augmented Reality Learning Media

Figure 3. Augmented Reality Visualization of Flat-Sided Solid Geometry

Expert validation

Before implementation, two material experts and two media experts appraised the product. The material review placed the medium in the very feasible category, indicating sound content accuracy and instructional relevance (Table 4).

Table 4. Material Expert Validation Results

Validator	Score (%)	Category
Material Expert 1	96	Very feasible
Material Expert 2	91	Very feasible
Average	**93.5**	**Very feasible**

The media review likewise reported a high level of feasibility, with the strongest marks for readability, program management, and documentation quality (Table 5).

Table 5. Media Expert Validation Results

Validator	Score (%)	Category
Media Expert 1	100	Very feasible
Media Expert 2	94	Very feasible
Average	**97**	**Very feasible**

Read against the criteria in Table 2, both reviews sit firmly in the very feasible band, and the closeness of the two validators' scores within each panel suggests that the judgements were stable rather than idiosyncratic. The material panel's high marks bear on the soundness of the content and its fit with the eighth-grade curriculum, while the media panel's marks speak to the application's usability and technical reliability, two qualities that must hold together for an AR medium to function in a real classroom. These figures index expert-judged feasibility only. They are not measures of student learning and should not be read as evidence of achievement gains.

Two mathematics teachers then evaluated the medium as practitioners and judged it highly suitable for classroom use (Table 6).

Table 6. Practitioner Validation Results

Validator	Score (%)	Category
Practitioner 1 (Teacher)	92	Very practical
Practitioner 2 (Teacher)	97	Very practical
Average	**94.5**	**Very practical**

Implementation

Implementation comprised a small-group trial with 12 students and a field trial with 34 students. The small-group trial functioned as a controlled first exposure. Working with a limited number of learners allowed the researchers to observe how students handled the image targets, navigated between features, and reacted to the AR display, and to record any friction before scaling up. Every assessed aspect (interface attractiveness, AR visualization quality, ease of use, responsiveness, learning support, motivation, and learning independence) was rated Very Good. Students remarked that the medium was easy to operate and that manipulating the solids helped them grasp geometric concepts more readily than reading static figures.

The field trial then tested the medium under more realistic classroom conditions with a larger group. The pattern of responses held: learners again described the medium as attractive, practical, and useful for studying flat-sided solid geometry, and several singled out the net-folding visualization as the feature that clarified a relationship they had previously found confusing. The consistency between the two trials, across different group sizes and settings, strengthens confidence that the favourable ratings reflect the medium itself rather than the circumstances of a single session. These trials measured usability and practicality (user acceptance), not learning outcomes. The positive ratings therefore indicate that students found the medium easy and helpful to use, not that measured understanding improved.

DISCUSSION

Meeting the Identified Needs Through Targeted Design

The results suggest that the developed AR medium was well matched to the instructional challenges pinpointed during needs analysis. The difficulty students faced in visualizing three-dimensional solids was addressed by interactive AR displays that let them observe and manipulate each figure directly. This outcome speaks to the study's central aim of supporting spatial visualization and conceptual understanding, and it aligns with reviews reporting that AR strengthens spatial visualization in geometry learning (Nadzeri et al., 2024; Yang et al., 2025), as well as with experimental work showing that AR- and VR-based geometry tools improve visualization, retention, and performance (Gargrish et al., 2021; Su et al., 2022). Because the present study did not measure learning, these parallels are offered as context rather than as evidence that our medium produced comparable gains. By turning an abstract solid into something learners can turn over in real space, the medium narrows the gap between a printed figure and the object it represents.

A further point concerns the alignment between the difficulty identified at the outset and the feature designed to address it. The needs analysis isolated the net-to-solid transition as the crux of students' trouble, and the application's net-representation function was built specifically to externalise that transition. That students in both trials singled out this feature as clarifying suggests the design logic held end to end: a documented problem led to a targeted affordance, which learners then experienced as helpful. This traceability, from need through design to user response, is one of the advantages of building within a structured ADDIE process rather than assembling features opportunistically.

Why the Medium was Rated Highly: Content, Technical Quality, and Practicality

The high material-validation scores indicate that the medium satisfied requirements of content accuracy, completeness, instructional relevance, and curricular alignment. Experts likely rated the content highly because it was built directly from the eighth-grade curriculum and revised in response to their own comments on definitions and worked examples, which tightened the fit between content and standards. Embedding learning materials, concept-understanding questions, and practice exercises in one application let students move through the topic in a coherent sequence rather than juggling separate resources. This integration suggests that the product is not merely a visualization tool but a support for meaningful, structured learning, an interpretation consistent with the view that well-designed digital media translate abstract content into accessible representations (Hafizah, 2023). The design also heeded the caution raised in cognitive-load reviews that AR aids work best when they follow established multimedia-learning principles rather than adding visual novelty for its own sake (Buchner et al., 2022; Ceken & Taşkın, 2025).

The media-validation results corroborate the application's technical quality. Strong marks for readability, usability, interface design, program management, and documentation show that the build honoured established principles of educational-media design. From a cognitive standpoint, the medium supports spatial cognition by distributing the mental work of imagining a solid across the real and virtual fields: instead of holding and rotating a figure entirely in the mind, students offload part of that transformation onto the AR display and manipulate it by hand, which cognitive-load accounts associate with reduced extraneous load and freed working memory (Ahmad & Siller, 2024). Whereas many conventional geometry resources rest on static two-dimensional drawings, this application invites students to engage three-dimensional objects dynamically and to inspect their structure from several angles. Comparable studies that introduced interactivity into geometry learning likewise report gains in students' responses and engagement (Rohendi et al., 2025), reinforcing the idea that interaction, not display alone, is what makes such media effective.

The media-validation results corroborate the application's technical quality. Strong marks for readability, usability, interface design, program management, and documentation show that the build honoured established principles of educational-media design. From a cognitive standpoint, the medium supports spatial cognition by distributing the mental work of imagining

a solid across the real and virtual fields: instead of holding and rotating a figure entirely in the mind, students offload part of that transformation onto the AR display and manipulate it by hand, which cognitive-load accounts associate with reduced extraneous load and freed working memory (Ahmad & Siller, 2024). Whereas many conventional geometry resources rest on static two-dimensional drawings, this application invites students to engage three-dimensional objects dynamically and to inspect their structure from several angles. Comparable studies that introduced interactivity into geometry learning likewise report gains in students' responses and engagement (Rohendi et al., 2025), reinforcing the idea that interaction, not display alone, is what makes such media effective.

Contribution and How the Findings Extend Prior Research

These results also belong in the wider research conversation on AR in geometry. Studies focused specifically on nets and solids report that AR helps learners coordinate a figure's two-dimensional and three-dimensional forms (Pakpahan et al., 2023), and effectiveness studies at the junior secondary level find gains in geometric thinking when AR is introduced (Pujiastuti & Haryadi, 2024). At the elementary level, performance evaluations of AR geometry tools point in the same direction (Tarng et al., 2024), and systematic reviews of AR game-based learning in STEM report broadly positive learning effects (Yu et al., 2022). The present study's feasibility and practicality evidence dovetails with this body of work. It suggests that the qualities reviewers and students valued here (interactivity, clear visualization, ease of use) are the same qualities that, in effectiveness studies, translate into measurable learning gains.

The new knowledge this study contributes is therefore less a further demonstration that "AR helps geometry" and more a validated design case. It shows how a specific, documented difficulty (the net-to-solid transition) can be mapped, through a disciplined ADDIE process, onto a specific AR affordance (dynamic net representation) within a single Unity application that unifies all four flat-sided solids. In doing so it extends prior work that treated outcome measurement and technical performance separately by supplying a traceable link from need to design that other developers can reuse. Set against earlier work, the contribution is twofold. Methodologically, it delivers a comprehensive Unity-based AR application produced through a disciplined ADDIE process rather than an ad hoc build, so that each design choice traces back to a documented need. Substantively, the application unites several solids and adds interactive features, object manipulation, and net representation that distinguish it from AR resources offering only static models.

Limitations and Future Work

Several limitations bound these claims. First, and most importantly, the study evaluated only the feasibility and practicality of the medium. It did not test effectiveness, so no claim is made that the medium improved achievement, spatial visualization, or higher-order thinking. Second, the evidence rests on a single school (SMP Negeri 10 Tasikmalaya) with a small sample (12 students in the pilot and 34 in the field trial) and no control or comparison group, which limits generalisability. Third, the practicality data are self-reported user responses gathered immediately after use and may reflect novelty effects rather than durable learning value. Fourth, the marker-based Unity and Vuforia pipeline depends on printed image targets, adequate lighting, and compatible Android devices, so performance may vary in other classroom settings. Future research should therefore test the medium's effectiveness through experimental or quasi-experimental designs with larger, more varied samples and control groups, measure spatial-visualization and achievement gains with validated instruments, and examine retention over time as well as the medium's behaviour across different devices and lighting conditions.

CONCLUSION AND SUGGESTIONS

This study developed a Unity-based Augmented Reality learning medium for teaching flat-sided solid geometry using the ADDIE model. The evaluation results indicate that the developed medium meets the expected standards of feasibility and practicality and was positively received by both teachers and learners. These findings suggest that the medium can serve as a viable technology-enhanced resource for supporting mathematics instruction, particularly by providing interactive three-dimensional representations of geometric objects that are otherwise difficult to visualize through conventional media.

The study contributes to mathematics education by offering a technology-enhanced solution that brings Augmented Reality and Unity into geometry instruction. In practical terms, the medium gives teachers an alternative resource that can enliven classroom learning. In theoretical terms, it adds to the evidence that carefully designed AR can facilitate the learning of abstract mathematical ideas through interactive three-dimensional visualization. Several limitations should temper these conclusions, as detailed in the Discussion: the trial was confined to a single school with a modest, uncontrolled sample, and the evaluation centred on feasibility and practicality rather than on learning gains. Future research should test the medium's effectiveness for achievement, spatial reasoning, and higher-order thinking through experimental designs with larger and more varied samples, and should examine retention and cross-device robustness. More broadly, teachers are encouraged to weave AR media into mathematics instruction, schools to provide the necessary technological infrastructure, and policymakers to support the integration of emerging technologies into the mathematics curriculum.

ACKNOWLEDGEMENTS

The authors would like to thank the principal, mathematics teachers, and eighth-grade students of Public Junior High School (SMP Negeri) 10 Tasikmalaya for their participation and cooperation during the data collection and product trials. The authors also gratefully acknowledge the material and media experts, as well as the practitioner-teachers, for their constructive feedback during the validation of the learning media, and the Department of Mathematics Education, Universitas Siliwangi, for its academic support throughout this study.

REFERENCES

Ahmad, S., & Siller, H.-S. (2024). Investigating the effect of manipulatives on mathematics achievement: The role of concrete and virtual manipulatives for diverse achievement level groups. *Journal on Mathematics Education, 15*(3), 979–1002. https://doi.org/10.22342/jme.v15i3.pp979-1002

Ateş, H., & Garzón, J. (2023). An integrated model for examining teachers' intentions to use augmented reality in science courses. *Education and Information Technologies, 28*(2), 1299–1321. https://doi.org/10.1007/s10639-022-11239-6

Avila-Garzon, C., Bacca-Acosta, J., Kinshuk, Duarte, J., & Betancourt, J. (2021). Augmented reality in education: An overview of twenty-five years of research. *Contemporary Educational Technology, 13*(3), ep302. https://doi.org/10.30935/cedtech/10865

Buchner, J., Buntins, K., & Kerres, M. (2022). The impact of augmented reality on cognitive load and performance: A systematic review. *Journal of Computer Assisted Learning, 38*(1), 285–303. https://doi.org/10.1111/jcal.12617

Çeken, B., & Taşkın, N. (2025). Examination of multimedia learning principles in augmented reality and virtual reality learning environments. *Journal of Computer Assisted Learning, 41*(1), e13097. https://doi.org/10.1111/jcal.13097

Eryigit, C. D, Kucuk, S., & Tasgin, A. (2025). Impact of augmented reality technology on geometry skills and motivation of preschool children. *Education and Information Technologies*, *30*(16), 22753–22778. https://doi.org/10.1007/s10639-025-13631-4

Elford, D., Lancaster, S. J., & Jones, G. A. (2022). Exploring the effect of augmented reality on cognitive load, attitude, spatial ability, and stereochemical perception. *Journal of Science Education and Technology*, *31*(3), 322–339. https://doi.org/10.1007/s10956-022-09957-0

Flavin, E., Hwang, S., & Flavin, M. T. (2025). Augmented Reality for Mathematics Achievement: A Meta-Analysis of Main and Moderator Effects: Flavin et al. *International Journal of Science and Mathematics Education*, *23*(7), 2305–2330. https://doi.org/10.1007/s10763-025-10546-x

Gargrish, S., Kaur, D. P., Mantri, A., Singh, G., & Sharma, B. (2021). Measuring effectiveness of augmented reality-based geometry learning assistant on memory retention abilities of the students in 3D geometry. *Computer Applications in Engineering Education*, *29*(6), 1811–1824. https://doi.org/10.1002/cae.22424

Hafizah, N. (2023). Media Pembelajaran Digital Generasi Alpha Era Society 5.0 Pada Kurikulum Merdeka [Digital Learning Media for Generation Alpha in the Society 5.0 Era within the Independent Curriculum]. *Al-Madrasah: Jurnal Ilmiah Pendidikan Madrasah Ibtidaiyah*, *7*(4), 1675–1688. https://doi.org/10.35931/am.v7i4.2699

Herman, H., Zalukhu, A., Hulu, D. B. T., Zebua, N. S. A., Manik, E., & Situmorang, A. S. (2023). Augmented reality (AR) pada geogebra meningkatkan kemampuan spasial dan pemecahan masalah matematis pada materi dimensi tiga [Augmented reality (AR) in GeoGebra enhances spatial and mathematical problem-solving abilities regarding three-dimensional topics]. *Journal on Education*, *5*(3), 6032–6039. https://doi.org/10.31004/joe.v5i3.1368

Hidayat, R., Samsudin, S., Wang, X., & Rahman, S. N. A. (2026). Augmented Reality in Science, Technology, Engineering and Mathematics Education: A Meta-Analysis. *Journal of Computer Assisted Learning*, *42*(1), e70164. https://doi.org/10.1002/jcal.70164

Hrp, F. P. L., Ibna, F. A., Purba, T., Panjaitan, A., Saragih, L. D., Abyansyah, N., & Sihombing, W. L. (2025). Analisis miskonsepsi geometri bangun datar dan bangun ruang pada buku matematika tingkat SMP sederajat [Analysis of misconceptions regarding 2D and 3D shapes in mathematics textbooks for the junior high school level (or equivalent)]. *Pendas: Jurnal Ilmiah Pendidikan Dasar*, *10*(03), 260–273. https://journal.unpas.ac.id/index.php/pendas/article/view/33388/16877

Hussain, A., Shakeel, H., Hussain, F., Uddin, N., & Ghouri, T. L. (2020). Unity game development engine: A technical survey. *Univ. Sindh J. Inf. Commun. Technol*, *4*(2), 73–81. https://sujo.usindh.edu.pk/index.php/USJICT/article/view/1800

Kifthiyyah, M., Hariastuti, R. M., Listiwikono, E. (2024). Kemampuan visual spasial siswa smp pada materi bangun ruang sisi datar ditinjau dari jenis kelamin [Visuospatial abilities of junior high school students regarding solid shapes with flat faces, analyzed by gender]. *Differential: Journal on Mathematics Education*, *1*(2), 110–125. https://doi.org/10.32502/differential.v1i2.102

Lee, W. W., & Owens, D. L. (2004). *Multimedia-based instructional design: Computer-based training, web-based training, distance learning* (2nd ed.). Pfeiffer

Li, G., Luo, H., Chen, D., Wang, P., Yin, X., & Zhang, J. (2025). Augmented reality in higher education: A systematic review and meta-analysis of the literature from 2000 to 2023. *Education Sciences*, *15*(6), 678. https://doi.org/10.3390/educsci15060678

Ma'rufi, M., & Alam, S. (2025). Analisis kesulitan siswa dalam menyelesaikan masalah bangun ruang sisi datar ditinjau dari gaya kognitif field independent [Analysis of students' difficulties in solving problems involving polyhedra with flat faces, viewed from a field-independent cognitive style]. *Proximal: Jurnal Penelitian Matematika Dan Pendidikan Matematika*, *8*(2), 653–664. https://doi.org/10.30605/proximal.v8i2.6065

Nadzeri, M., Musa, M., Cheng Meng, C., & Ismail, N. (2024). The effects of augmented reality geometry learning applications on spatial visualization ability for lower primary school pupils. *International Journal of Interactive Mobile Technologies, 18*(16), 104–118. https://doi.org/10.3991/ijim.v18i16.47079

Nazarudin, M. F., Asmoro, D. P. T., & Sianipar, A. Z. (2024). Pembuatan aplikasi mobile augmented reality untuk visualisasi rumah adat berbasis Unity [Development of a Unity-based mobile augmented reality application for visualising traditional houses]. *Jurnal Manajemen Informatika Jayakarta,* *4*(4), 315–342. https://doi.org/10.52362/jmijayakarta.v4i4.1615

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

Ozcakir, B., & Cakiroglu, E. (2021). An augmented reality learning toolkit for fostering spatial ability in mathematics lesson: Design and development. *European Journal of Science and Mathematics Education, 9*(4), 145–167. https://doi.org/10.30935/scimath/11204

Pakpahan, S. P., Sapta, A., & Nisa, U. K. (2023). Development of augmented reality in understanding the nets and ribs of spatial buildings. *Jurteksi, 10*(1), 115-122. https://doi.org/10.33330/jurteksi.v10i1.2972

Papakostas, C., Troussas, C., Krouska, A., & Sgouropoulou, C. (2022). Personalization of the learning path within an augmented reality spatial ability training application based on fuzzy weights. *Sensors, 22*(18), 7059. https://doi.org/10.3390/s22187059

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

Riduwan, M. B. A. (2022). *Skala pengukuran variabel-variabel penelitian [Measurement scales of research variables*]. Alfabeta

Rodriguez-Saavedra, M. O., Benavides, L. G. B., Galindo, I. C., Ascuna, L. M. C., Gonzales, A. V. M., López, J. W. M., & Arguedas-Catasi, R. W. (2025). Augmented reality as an educational tool: Transforming teaching in the digital age. *Information, 16*(5), 372. https://doi.org/10.3390/info16050372

Rohendi, D., Ramadhan, M. O., Syrene, S., Rahim, A., Zulnaedi, H. (2025). Enhancing students' interactivity and responses in learning geometry by using augmented reality. *Eurasia Journal of Mathematics, Science and Technology Education, 21*(1), em2559. https://doi.org/10.29333/ejmste/15796

Su, Y.-S., Cheng, H.-W., & Lai, C.-F. (2022). Study of virtual reality immersive technology enhanced mathematics geometry learning. *Frontiers in Psychology, 13*, 760418. https://doi.org/10.3389/fpsyg.2022.760418

Tarng, W., Huang, J.-K., & Ou, K.-L. (2024). Improving elementary students' geometric understanding through augmented reality and its performance evaluation. *Systems, 12*(11), 493. https://doi.org/10.3390/systems12110493

Uriarte-Portillo, A., Zataraín-Cabada, R., Barrón-Estrada, M. L., Ibáñez, M., & González-Barrón, L.-M. (2023). Intelligent augmented reality for learning geometry. *Information, 14*(4), 245. https://doi.org/10.3390/info14040245

Voulgari, N., Panagopoulos, M., & Garneli, V. (2025). A systematic review of augmented reality in mathematics education: Fostering learning through art integration. *Arts & Communication, 3*(2), 4446. https://doi.org/10.36922/ac.4446

Wong, J., Yu, K., & Giacaman, N. (2021). Scaffolding spatial ability with augmented reality and virtual reality. *International Journal of Mobile Learning and Organisation, 15*(1), 50–69. https://doi.org/10.1504/ijmlo.2021.111597

Yang, Y., Wenfei, D., Mavrikis, M., & Geraniou, E. (2025). Spatial skill development through augmented reality in mathematics education: A scoping review. *Digital Experiences in Mathematics Education, 12, 277–310.* https://doi.org/10.1007/s40751-025-00187-8

Yu, J., Denham, A. R., & Searight, E. (2022). A systematic review of augmented reality game-based learning in STEM education. *Educational Technology Research and Development, 70*(4), 1169–1194. https://doi.org/10.1007/s11423-022-10122-y