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Strengthening Deep Learning: Developing an Ethnomathematics–Collaborative Augmented Reality (ME-CAR) Module to Optimize Numeracy Skills and Self-Regulated Learning

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Abstract

Indonesian junior high school students' persistent low numeracy and limited autonomy necessitate culturally grounded, technology-enhanced learning media. This study developed an Ethnomathematics–Collaborative Augmented Reality Module (ME-CAR) using Educational Design Research with the ADDIE model. The module underwent expert validation (I-CVI $\geq$ 0.83; S-CVI = 0.92; $\alpha = 0.89$), small-scale practicality testing ($n = 20, 91.26\%$), and large-scale testing ($n = 35, 92.01\%$), all rated excellent. Effectiveness was examined through a quasi-experimental pretest–posttest control-group design (experimental $n = 35$; control $n = 34$). The experimental group's numeracy improved significantly ($36.00 \rightarrow 87.68$) compared to the control ($34.88 \rightarrow 62.00$). ANCOVA confirmed a strong treatment effect ($F(1,67) = 18.21, p < 0.001, \eta p^2 = 0.214$; $d = 2.15$). Reliable instruments ($\alpha \geq 0.81 - 0.87$) supported findings. By integrating ethnomathematics, collaborative AR, and self-regulated learning, ME-CAR uniquely enhances numeracy, autonomy, and contextualized understanding of three-dimensional geometry, contributing a novel digital solution in mathematics education.

Keywords: *ethnomathematics; augmented reality; numeracy; self-regulated learning; deep learning*

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INTRODUCTION

The transformation of 21st-century education demands that students possess higher-order thinking skills, numeracy competence, and self-regulated learning capabilities (Ansari et al., 2021) to adapt within a digital society driven by information and technology (OECD, 2023). Nevertheless, the 2022 PISA report underscores that 71% of Indonesian students remain below Level 2 in numeracy (Yulianto et al., 2024; Afgani & Paradesa, 2021). Such a poor level of performance negatively impacts students' capacity to interpret information, employ logical reasoning, and make data-informed decisions in daily life (Tanujaya et al., 2021). Level 2 is regarded as the minimum threshold for independently and flexibly using mathematics in real-life situations (OECD, 2023). These results reveal serious deficiencies in problem-solving and reflective thinking, largely attributed to conventional pedagogies that focus on rote memorisation, lack conceptual understanding, and are decontextualised (Yulianto et al., 2024; Asyari et al., 2024). Teacher-centred approaches that marginalise students' active engagement in meaning-making processes continue to hinder the development of numeracy and self-regulated learning (Emanet & Kezer, 2021; Wiedbusch et al., 2021). Recent studies report that only 18% of Indonesian teachers consistently facilitate reflective, problem-based, or contextual learning, primarily due to limited training in reflective pedagogy and insufficient contextual learning resources (Diamah et al., 2022). A paradigm shift is therefore urgently required towards constructivist, reflective, and transformative learning that fosters deep cognitive engagement, meaningful numeracy development, and enhanced learner autonomy.

Deep learning in education encompasses the ability to develop a profound understanding, integrate ideas, transfer knowledge to new contexts, and reflect on learning processes metacognitively (Sarker, 2021; Tanujaya et al., 2021). Yet Indonesian mathematics classrooms remain dominated by surface-level learning practices characterised by memorisation, minimal contextualisation, and procedural orientation (Yulianto et al., 2024). This gap is reflected in PISA 2022 scores, where Indonesian students average only 379, far below the OECD mean of 489 (OECD, 2023). Over 70% of Indonesian students can solve only Level 1 and 2 numeracy problems, which generally require basic arithmetic and geometry with little demand for mathematical modelling or reflective reasoning (Yulianto et al., 2025). Higher-level indicators such as analysing indirect contextual data, formulating problem-solving strategies, and applying mathematical modelling in novel situations remain largely unachieved (Tanujaya et al., 2021). This situation carries serious implications for decision-making literacy, employability readiness, and active participation in a data-driven society.

Numeracy encompasses not only computational skills but also logical reasoning, data interpretation, and context-based decision making (Geiger et al., 2015). However, the conceptual separation between numeracy and mathematical literacy in the Indonesian curriculum, despite their theoretical overlap in both conceptual and operational dimensions (Fanggidae et al., 2024), has resulted in a lack of alignment among curriculum, assessment, and pedagogy. The absence of a coherent national numeracy framework creates inconsistencies in assessment and hampers the design of culturally contextualised pedagogical approaches, consequently contributing to students' poor performance in real-world contexts measured by PISA (OECD, 2023). The 2022 INAP Survey involving over 13,000 fifth-grade students revealed that only 18% were able to interpret mathematical information in context – a clear indication of weak functional numeracy (Aisyah & Juandi, 2022). Universal numeracy approaches often fail to capture students' culturally specific ways of knowing, even though the integration of local culture has been shown to enhance the meaningfulness and relevance of numeracy learning.

Empirical studies highlight that *Problem-Based Learning* (PBL) and technological tools such as MathCityMap can improve student engagement and conceptual understanding within basic mathematical literacy tasks (Cahyono et al., 2023; Rehman et al., 2024). Nevertheless, their effectiveness in fostering higher-order thinking skills, particularly analytical and synthetic aspects of functional numeracy, remains limited (Tanujaya et al., 2021). Yulianto et al. (2024), for example, reported that only 22% of students could solve numeracy tasks at Level 4 and above even after receiving PBL interventions. Moreover, MathCityMap is inherently location-based and spatial; it lacks reflective cognitive elements and cultural contextualisation, resulting in limited conceptual connection. While useful for visualisation, prior research indicates that MathCityMap remains surface-oriented, inadequately supporting self-regulation and transfer of learning to real-life contexts (Gurjanow et al., 2019; Milicic et al., 2020). Consequently, there is a critical need for instructional designs that not only provide contextualised problems but also enhance intrinsic motivation, cognitive regulation, and meaningful cultural engagement.

One of the key strategic approaches that supports deep learning is Self-Regulated Learning (SRL), which encompasses goal setting, strategic planning, ongoing monitoring, and reflective evaluation of learning outcomes (Cerón et al., 2020; Fayaza & Ahangama, 2024). Recent empirical studies have demonstrated that SRL contributes positively to mathematical achievement, particularly in numeracy and higher-order problem solving (Lai & Hwang, 2021; Ansari et al., 2021). However, national-level surveys by the Ministry of Education, Culture, Research and Technology (2020) revealed that fewer than 30% of Indonesian students consistently exhibit high levels of self-regulation in learning mathematics, largely due to a lack of teacher training, weak classroom reflective culture, and limited availability of technology-based learning resources. Moreover, SRL has not yet been explicitly embedded in contextual learning designs that incorporate students' cultural backgrounds, even though integrating local values has been proven to enhance engagement and mathematical identity (Lidinillah et al., 2022; Ishartono et al., 2022). For instance, locally based numeracy tasks can be used not only as cultural illustrations but also as reflective media within SRL phases, such as self-monitoring and goal setting. Accordingly, there is a need for a pedagogical model that explicitly combines SRL, immersive technology, and cultural context so that SRL becomes an instructionally facilitated process within mathematics education, rather than merely a personal skill.

Ethnomathematics, understood as culturally embedded mathematical knowledge (Batiibwe, 2024; Kusuma et al., 2024), represents mathematical concepts through contexts drawn from students' everyday lived experiences, thereby strengthening the connection between abstract ideas and real-world phenomena (Putra et al., 2024; Susanta et al., 2023; Ramadhan et al., 2024). Recent evidence suggests that integrating ethnomathematics into classroom practice enhances cognitive and affective engagement while supporting the development of functional numeracy (Pratama & Yelken, 2024; Lidinillah et al., 2022; Sunzuma & Umbara, 2025). When combined with Collaborative Augmented Reality (AR) technology, ethnomathematical materials can be spatially and interactively visualised, enabling learners to construct knowledge through multi-modal and contextualised learning environments (Yegorina et al., 2021; Schutera et al., 2021). Nindiasari et al. (2024) further highlighted that collaborative AR significantly enhances self-regulation, conceptual understanding, and transfer of learning. Consequently, the development of the Ethnomathematics–Collaborative Augmented Reality Module (ME-CAR) is proposed as an innovative, data-driven solution to address students' low numeracy skills and limited SRL by integrating cultural context, immersive technology, and principles of digital constructivism.

Recent studies indicate that research on technological integration in mathematics education remains largely fragmented. Augmented Reality (AR)–based investigations tend to concentrate on visualization and learning motivation (Amores-Valencia et al., 2022; Ziden et al., 2022), without holistically incorporating aspects of self-regulated learning (SRL) or cultural contextualization. Conversely, the development of ethnomathematics-based learning materials has predominantly focused on cultural relevance, lacking interactive technological enhancement (Batiibwe, 2024; Kusuma et al., 2024). A comprehensive review by Sunzuma and Umbara (2025) further highlighted the absence of learning models that integrate SRL, contextual numeracy, localized cultural values, and AR-based technologies into a single validated instructional design. This reveals a significant research gap, particularly in the development of innovative learning modules that are not only valid and practical but also have a measurable impact on enhancing students' functional numeracy and self-directed learning skills in the digital era.

The main issue addressed in this research lies in the limited integration of local cultural context, Augmented Reality (AR) technology, and self-regulated learning (SRL) approaches in mathematics instruction. Hsu & Liu (2023) observed that AR in education is still broadly perceived as a visual aid, rather than a means to foster student reflection or learning autonomy. Simultaneously, the incorporation of ethnomathematical values into teaching has not been systematically directed toward promoting SRL strategies such as goal setting, self-monitoring, and self-evaluation (Ansari et al., 2021; Wang & Sperling, 2020). To date, there is no instructional framework that explicitly integrates these three elements into one learning module that can independently foster culturally-based functional numeracy. Hence, a pedagogical design grounded in sociocultural constructivism (Alkhudiry, 2022) is required, one that is not only culturally situated but also digitally interactive and cognitively reflective to optimize meaningful learning experiences that are data-driven and adaptive to 21st-century learner characteristics.

The solution proposed in this study is the development of the Ethnomathematics–Collaborative Augmented Reality Module (ME-CAR), an innovative instructional approach that integrates local cultural contexts, collaborative augmented reality technology, and principles of self-regulated learning (SRL) into a unified design. The module employs a multimodal format utilizing AR-based visual-spatial representations, culturally contextual narratives, and reflective-metacognitive activities structured around SRL phases as outlined by Brenner (2022): forethought, performance, and self-reflection. Each learning task within ME-CAR engages students collaboratively in solving numeracy challenges rooted in indigenous knowledge and visualized through augmented reality (Hsu & Liu , 2023; Ansari et al., 2021; Wang & Sperling, 2020). The module was developed using the ADDIE model and validated by experts in subject matter, media, and pedagogy to ensure content, construct, and implementation feasibility (Muliana et al., 2023). Through this design, ME-CAR not only enhances students' functional numeracy but also strengthens independent learning strategies by stimulating self-regulation and authentic knowledge transfer. However, despite the growing body of research on Problem-Based Learning, MathCityMap, and ethnomathematics-based instruction, prior approaches remain fragmented and limited, focusing either on contextualisation without technological interactivity or on AR visualisation without embedding reflective self-regulated learning strategies. No existing instructional model has systematically integrated local cultural contexts, immersive collaborative AR, and structured SRL phases into a single validated framework for numeracy learning. This unresolved gap in the literature represents a critical barrier to advancing both functional numeracy and learner autonomy in Indonesian classrooms, and it is precisely this gap that the present study addresses through the development of the ME–CAR module.

The objective of this research is to develop a theoretically and empirically validated Ethnomathematics–Collaborative Augmented Reality (ME-CAR) module aimed at improving students' functional numeracy based on local cultural contexts and enhancing their self-regulated learning capacity through the integration of metacognitive, motivational, and behavioral strategies. The module is grounded in principles of digital constructivism and multimodal learning, and is evaluated according to content validity, practical implementation, and empirical effectiveness through both limited and extensive trials. Emphasis is placed on elevating students' cognitive engagement toward higher-order thinking skills and promoting numeracy transfer in authentic contexts, thereby reinforcing deep learning aligned with the demands of the *Merdeka* Curriculum and global literacy frameworks.

METHODS

This study employed an Educational Design Research (EDR) approach, which has been proven effective for developing culturally based digital instructional media (Muliana et al., 2023). The primary aim was to develop an innovative instructional module grounded in Ethnomathematics–Collaborative Augmented Reality (ME–CAR) to enhance students' numeracy skills and self-regulated learning (SRL). The development process adopted the ADDIE model (Analysis, Design, Development, Implementation, Evaluation), chosen for its systematic yet flexible structure and its success in guiding the development of culturally based digital media (Muliana et al., 2023; Hidayat et al., 2023). Through this model, an interactive ME–CAR module was produced and rigorously validated to ensure its content validity, practicality in classroom implementation, and empirical effectiveness in improving students' numeracy performance and SRL.

The overall methodological framework combined Educational Design Research (EDR) with a quasi-experimental research design. Specifically, the implementation stage employed a non-equivalent control group pretest–posttest design (Fraenkel & Wallen, 2019; Creswell, 2018). This design was chosen because random assignment was not feasible at the classroom level, yet it allowed for rigorous comparison between an experimental group (using the ME–CAR module) and a control group (conventional instruction). The pretest–posttest structure enabled the measurement of learning gains, while ANCOVA was used to statistically control for baseline differences. The integration of EDR with quasi-experimental testing ensured that both the *process of development* (validity and practicality) and the *product outcomes* (effectiveness) were systematically addressed.

In the analysis phase, a needs assessment was carried out through classroom observations, teacher interviews, and curriculum review using an exploratory qualitative approach. The participants consisted of four mathematics teachers and twenty-four eighth-grade students from SMP Negeri 2 Leuwidamar in the 2024/2025 academic year, who were preparing to study polyhedral geometry. The school was purposively selected due to students' numeracy achievement being below the minimum mastery criteria. Thematic analysis following Braun and Clarke (2022), supported by intercoder agreement (0.82) and source triangulation, revealed a misalignment between curricular demands and students' actual learning experiences. Furthermore, students demonstrated limited ability to reflect on their learning processes and regulate learning strategies. Teachers noted that numeracy materials were rarely contextualized in local settings, while students admitted that they had never connected geometric concepts with the traditional architecture they encountered daily. Observations further indicated that most students struggled to plan problem-solving strategies and seldom engaged in error reflection.

The design phase focused on formulating learning objectives, developing a culture-based numeracy concept map, and constructing Augmented Reality (AR) interaction scenarios. The design integrated the TPACK framework with Zimmerman's Self-Regulated Learning (SRL) model, aligning pedagogical and technological components with the phases of forethought, performance control, and self-reflection. Javanese cultural elements such as batik patterns, traditional musical instruments, and vernacular architecture were embedded in AR-based collaborative activities to foster visual exploration, problem-solving, and individual reflection. The instructional sequence was organized through a learning map and storyboard, including simulations built in Unity3D that enabled students to scan batik motifs and manipulate polyhedral representations.

The development phase produced the ME–CAR module using Unity3D, validated by six experts in content, media, and pedagogy. Three main products, the printed teaching script, the digital prototype, and the ethnomathematics-based AR component, were found to be highly valid (I-CVI $\geq$ 0.83; S-CVI $=$ 0.92; α $=$ 0.89). Revisions were made to clarify usage instructions, refine cultural contextualization, and simplify navigation within the application. The final product comprised a printed module containing learning objectives, SRL-based reflective activities, and AR exploration guides, complemented by a Unity3D application accessible via mobile devices.

Implementation was conducted on a limited scale in two public junior high schools in Lebak Regency using a quasi-experimental design. Expert validation, readability and practicality testing, and effectiveness evaluation were carried out in stages. The readability test involved 20 students, while the practicality test involved 35 students. The effectiveness trial engaged 70 students divided into experimental and control groups using a non-equivalent pretest–posttest design. Effectiveness was measured through a PISA-based numeracy test (α $=$ 0.81), an SRL questionnaire adapted from the MSLQ (α $=$ 0.87), and SRL activity observation sheets (κ $=$ 0.82). Data were analyzed using ANCOVA with normality and homogeneity assumption testing, along with effect size calculation using Cohen's d. The results showed significant differences between the experimental and control groups, with medium to large effect sizes, thereby confirming the module's effectiveness.

The final evaluation confirmed that the ME–CAR module meets the criteria of validity, practicality, and effectiveness for mathematics learning. Feedback from experts and end-users further enhanced the pedagogical quality, interactive navigation, and cultural contextualization of the product. Consequently, ME–CAR is not only technically feasible for classroom implementation but also pedagogically and contextually relevant in supporting 21st-century numeracy competencies among students in semi-urban Indonesian settings.

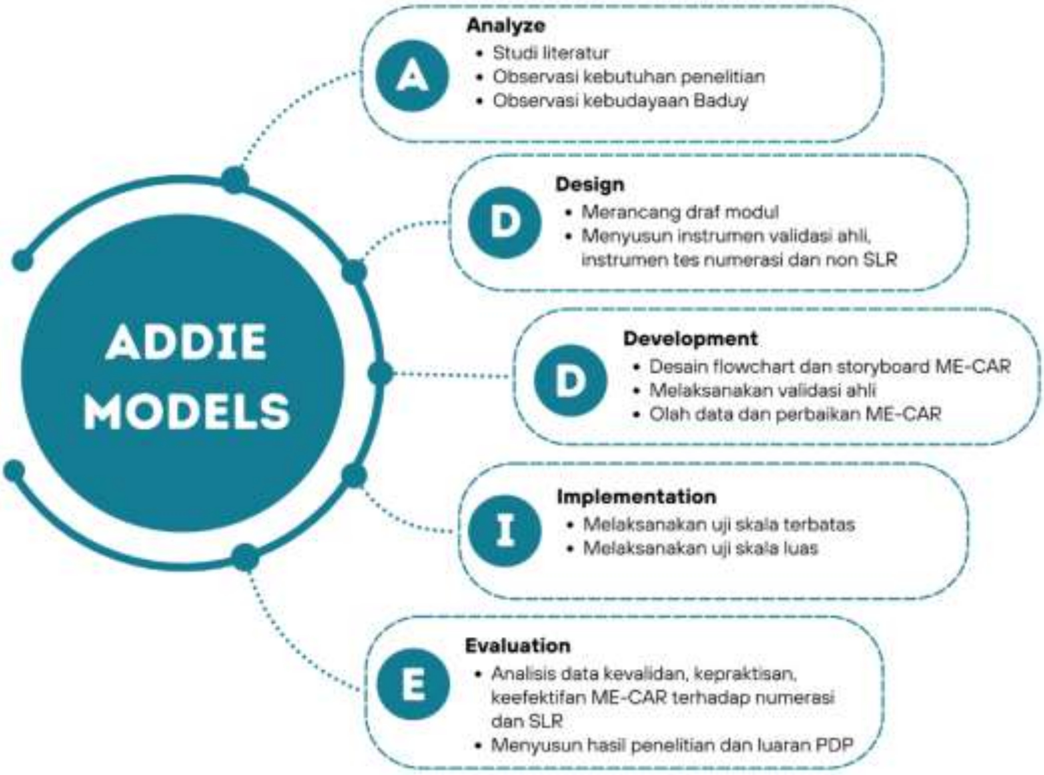

Figure 1. ADDIE Model

The data analysis techniques employed in this study incorporated both descriptive and inferential statistics. Normality was examined using the Shapiro–Wilk test, while homogeneity of variance was verified using Levene's test. Both assumptions were met ($p > .05$). Content validity was assessed using the Content Validity Index (CVI), with I-CVI values ≥ 0.83 and S-CVI $= 0.92$, indicating high validity (Lynn, 1986). Reliability was calculated using Cronbach's Alpha, with coefficients of .81 (numeracy test) and .87 (SRL questionnaire), both exceeding the recommended threshold of .70 for acceptable reliability (Nunnally & Bernstein, 1994). The analysis encompassed data gathered from content experts, instructional design experts, mathematics practitioners, and students. Descriptive statistics were used to calculate mean scores, percentages, and standard deviations, while inferential analysis, assisted by SPSS version 29, generated tabulations and graphical visualizations. The validity of the instructional module was examined based on evaluations from subject-matter experts, learning model experts, and mathematics teachers. Meanwhile, the practicality of the module was assessed using students' responses during implementation (see Table 1). Additionally, pre-test and post-test scores were utilized to support the evidence of effectiveness and were interpreted descriptively through a comparison of mean scores.

Table 1. Scoring Criteria, Validity Interpretation, and Practicality Interpretation of the Module

Score Weight	Assessment Interpretation	Validity Interpretation	Practicality Interpretation	Percentage Range
5	Excellent	Very Invalid	Excellent	80%–100%
4	Good	Less Valid	Good	60%–79%
3	Fair	Fairly Valid	Fair	40%–59%
2	Poor	Valid	Poor	20%–39%
1	Very Poor	Very Valid	Very Poor	0%–19%

The minimum criteria for a module to be regarded as valid and practical lie within the $80\% - 100\%$ range, based on expert validation results and field trials (Plomp & Nieveen, 2013). A module is considered effective if students' test results, both individually and in terms of classical completeness, achieve a mastery level of ≥ 75. Classical learning mastery is calculated using the following formula:

$$Mastery\ Learning\ Percentage = \frac{Number\ of\ students\ who\ achived\ mastery}{Total\ number\ of\ students} \times 100\%$$

RESULTS AND DISCUSSION

Analysis Stage

Survey results revealed that the majority of Grade VIII students perceive mathematics as a difficult subject, with 37% strongly agreeing and 23.33% agreeing, further reinforced by 48% acknowledging low academic achievement. In addition, 78% of students prefer printed learning modules, suggesting potential limitations in accessing or comfortably using digital media. Moreover, 19 students identified solid geometry as the most challenging topic, with 82% reporting the need for specific supporting tools to comprehend the material. This highlights that spatial visualization is a primary obstacle to mastering the topic, consistent with OECD (2023) and Asyari et al. (2024). Figure 2 reveals that the majority of Grade VIII students perceive mathematics as a difficult subject (37% strongly agree; 23.33% agree), further reinforced by their acknowledgment of low academic achievement (48% strongly agree). Figure 1 indicates that 78% of students prefer printed learning modules, suggesting potential limitations in accessing or comfortably using digital media. Figures 2 and 3 highlight that 19 students identified solid geometry as the most challenging topic, with 82% requiring specific supporting tools to comprehend the material. This indicates that spatial visualization remains a primary obstacle in mastering mathematics.

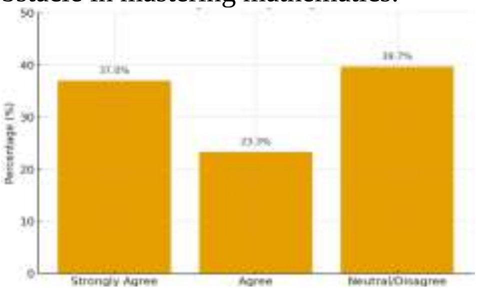

Figure 2. Students' Perceptions of Mathematics as a Difficult Subject

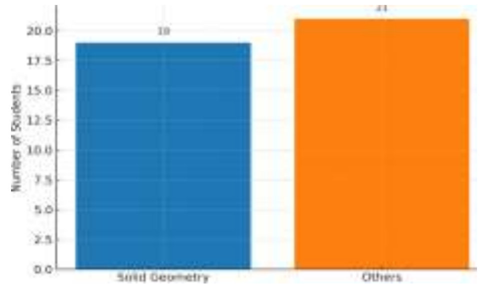

Figure 3. Distribution of Difficult Topics in Mathematics

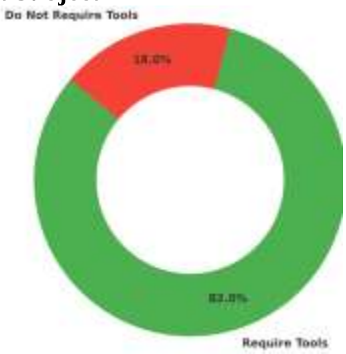

Figure 4. Students' Need for Supporting Tools in Learning Solid Geometry

Survey and triangulation results reveal that students' negative perceptions of mathematics are deeply rooted in instructional mechanisms affecting numeracy. Over one-third of respondents strongly agreed that mathematics is difficult (Figure 2, $n = 35$), while 78% preferred printed modules (Figure 3), reflecting digital access and literacy constraints rather than purely pedagogical choices. Solid geometry emerged as the most challenging topic, with 19 students identifying it and 82% indicating a need for specialized aids (Figures 3–4). Joint interpretation of quantitative data and teacher interviews shows three relational patterns: (1) mathematics anxiety and limited visual exposure correlate with low numeracy scores; (2) preference for printed modules is linked to device availability, requiring AR-based instruction to include non-digital options; and (3) reliance on manipulatives signals visual–spatial deficits that hinder higher-order problem solving. Thus, the challenges are conceptual (abstraction), affective (anxiety), access-related (digital divide), and cognitive (visual–spatial reasoning). These findings underscore the need for ME–CAR to: (a) adopt hybrid delivery (printed + QR/lightweight AR), (b) provide 3D manipulatives and exploratory tasks, and (c) embed structured SRL modules for metacognition and anxiety reduction (Zimmerman, 2002; Wang & Sperling, 2020). To reinforce these claims, statistical evidence should be reported, such as correlations between anxiety and numeracy, chi-square tests of media preference and access, and regression analyses on learning aids and visual–spatial scores. Such analyses, even if non-experimental, would strengthen the empirical basis for ME–CAR's design rationale.

They also emphasize that negative perceptions of mathematics frequently stem from limited visual and contextual learning experiences. Consequently, students' negative perceptions and low learning outcomes are not solely caused by the abstract nature of mathematics but also by students' inability to visualize spatial objects and by the scarcity of learning media that support independent exploration (Muliana et al., 2023). As a relevant solution, a printed-based instructional module focusing on solid geometry should be developed, equipped with simple 3D manipulative tools or exploratory worksheets designed using the ME-CAR framework (Assemblr Edu) in the context of traditional Baduy architecture, alongside structured reflective components intended to stimulate students' self-regulated learning (Zimmerman, 2002; Wang & Sperling, 2020). This module may be designed in a hybrid format with additional links to simple digital resources (e.g., QR-based animations) to accommodate diverse student preferences and levels of access. These findings highlight the need for culturally-based instructional media that support visual processing, such as ethnomathematics-based augmented reality modules (Afgani & Paradesa, 2021; Nindiasari et al., 2024; Ziden et al., 2022).

ME–CAR Module Design Stage

The design of the ME–CAR module began with a curriculum analysis of junior secondary school mathematics, emphasizing the topic of three-dimensional solid shapes. This topic was selected due to its strong potential for contextualisation through local cultural artefacts, such as traditional houses, carvings, and crafts, each rich in spatial-geometric elements. Embedding these ethnomathematical contexts is considered essential for bridging students' mathematical experiences with their daily surroundings (Afgani & Paradesa, 2021; Batiibwe, 2024). The analysis also critically referenced students' numeracy achievements and the need to enhance self-regulated learning (SRL) skills, addressing the persistent gap between conventional procedural, decontextualised instruction and the twenty-first-century mathematical literacy demands that prioritise cultural relevance, visualisation, and learner autonomy (OECD, 2023; Ansari et al., 2021).

An initial evaluation of five commercially available Year VIII mathematics textbooks revealed that only one included three-dimensional perspective images of solid figures, and none integrated ethnomathematical or local cultural artefacts to support conceptual understanding. These findings underscore students' limited exposure to spatial representations, which creates substantial barriers in constructing authentic and meaningful mathematical understanding (Wiedbusch et al., 2021; Nindiasari et al., 2024). To address this gap, an innovative approach integrating augmented reality, local cultural contexts, and structured SRL strategies was deemed essential, both pedagogically and psychologically. An empirical needs analysis was further conducted through a Focus Group Discussion with four mathematics teachers. The FGD identified three major challenges faced by students: (1) difficulty in visualising three-dimensional forms; (2) low understanding of spatial relationships among geometric components; and (3) limited ability to connect geometric concepts with real-life local objects. These issues reflect the broader findings of OECD (2023), indicating that weak spatial visualisation skills and the absence of local cultural relevance significantly contribute to low numeracy outcomes.

Based on these findings, ME–CAR was conceptualised with three systematically designed core components: (a) *Ethnomathematical contextualisation* incorporating cultural artefacts such as Baduy traditional houses, batik patterns, and musical instruments to concretely represent geometrical concepts (Afgani & Paradesa, 2021; Batiibwe, 2024); (b) *Augmented Reality (AR)* to develop interactive, collaborative three-dimensional visualisation and manipulation, which significantly enhances student motivation and learning outcomes (Amores-Valencia et al., 2022; Ziden et al., 2022); and (c) *SRL-based learning activities*, structured according to Zimmerman's (2002) three phases: *forethought* (goal-setting and motivational activation), *performance* (concept exploration and self-monitoring), and *self-reflection* (evaluation and metacognitive regulation), aligned with research emphasising the role of SRL in improving students' higher-level mathematical performance (Ansari et al., 2021; Wang & Sperling, 2020). By integrating these

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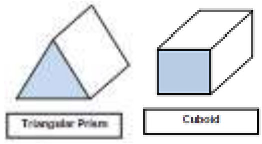
dimensions, the ME–CAR module seeks not only to overcome visual-conceptual barriers but also to reinforce learner autonomy and cultural connection in numeracy learning, in line with twenty-first-century mathematical literacy competencies (Geiger et al., 2015; Pratama & Yelken, 2024).

To obtain empirical needs analysis data, the researchers conducted a Focus Group Discussion (FGD) involving four mathematics teachers from the partner schools. The FGD identified several key student learning obstacles: (1) limited ability to visualise three-dimensional shapes, (2) inadequate understanding of spatial relationships among geometric elements, and (3) difficulty connecting abstract geometric concepts to concrete local objects. These findings corroborate OECD (2023), which asserts that spatial-visualisation barriers and the absence of local cultural context in mathematics instruction significantly contribute to students' low numeracy performance. In response, the ME–CAR module was developed through a systematic design process comprising three principal components: (a) integration of ethnomathematical contexts using local cultural artefacts, such as Baduy traditional houses, batik motifs, and musical instruments as realistic geometric representations, consistent with Afgani and Paradesa (2021) and Batiibwe (2024), who highlight the effectiveness of ethnomathematics in contextualising abstract mathematical concepts; (b) employment of Augmented Reality (AR) technology to foster interactive and collaborative spatial-visualisation, enabling students to manipulate complex 3D objects virtually an approach shown to enhance motivation and learning achievement (Amores-Valencia et al., 2022; Ziden et al., 2022); and (c) incorporation of Self-Regulated Learning (SRL)-based activities reflecting Zimmerman's (2002) three phases: *forethought* (activation of learning goals and motivation), *performance* (strategic conceptual exploration and self-monitoring), and *self-reflection* (evaluation of learning processes and outcomes), in line with Ansari et al. (2021) and Wang and Sperling (2020) emphasising the importance of SRL strategies for promoting autonomy and high levels of mathematical attainment. Through this integrative approach, the ME–CAR module addresses not only visual-conceptual challenges but also enhances students' self-regulation and cultural connectedness in numeracy learning, thereby responding to the demands of 21st-century mathematical literacy (Geiger et al., 2015; Pratama & Yelken, 2024).

Each unit of the module is structured progressively using a scaffolding approach beginning with the introduction of local cultural artefacts, then moving into the exploration of three-dimensional solid figures through a Collaborative Augmented Reality (AR) application, and concluding with numeracy-based reflective activities. Every unit includes clear learning objectives, contextual conceptual descriptions, AR exploration guidelines, and self-reflection worksheets designed to foster students' self-regulated learning (SRL). This approach is aligned with the findings of Wang and Sperling (2020) and Cerón et al. (2020), which underscore that embedding SRL strategies in technology-enhanced learning significantly improves students' independent and sustained mathematical learning outcomes. The instructional design adheres to multimodal learning principles (Trilling & Fadel, 2009), integrating visual (AR), social (collaborative discussions), and cultural (ethnomathematics) elements. Incorporating local cultural contexts such as batik patterns, traditional architectural forms, and other regional motifs aims to strengthen contextual mathematical literacy (Afgani & Paradesa, 2021; Batiibwe, 2024) while enhancing students' affective engagement and mathematical identity (Pratama & Yelken, 2024).

To ensure quality, the module underwent content validation by three experts: (1) a mathematics content specialist, (2) a digital pedagogy expert, and (3) an experienced mathematics teacher. The validation employed a qualitative rubric-based expert judgment method encompassing content validity, cultural appropriateness, and pedagogical implementability (Tanujaya et al., 2021). Revisions were then made based on expert feedback to guarantee the final design's coherence across mathematical content, cultural values, and SRL-oriented instructional strategies, by Vygotsky's sociocultural learning principles adapted for educational technology contexts (Alkhudiry, 2022).

<table>
<tr><th>The Leuit Lenggang</th><th>The Structure of the Leuit Lenggang</th><th>The Plane Figure</th></tr>
<tr><td rowspan="4"></td><td>The Roof of Leuit</td><td>
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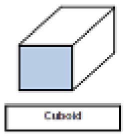
<tr><td>The Door of Leuit</td><td>
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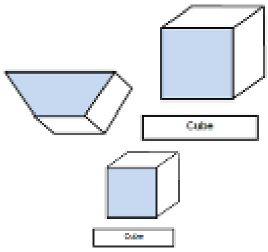
<tr><td>The Main Building of Leuit</td><td>
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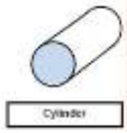
<tr><td>The Gelebeg of Leuit</td><td>
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</table>

Figure 5. Product Development

Development Stage

At this stage, the researchers designed and produced the *Ethnomathematics–Collaborative Augmented Reality (ME-CAR) Module*, to enhance students' functional numeracy and self-regulated learning (SRL) skills. The module was systematically developed using the ADDIE instructional design model, which has been widely recognised for its effectiveness in culturally based learning media development (Ziden et al., 2022; Afgani & Paradesa, 2021). During this process, local ethnomathematical numeracy content was constructed, and collaborative learning experiences were designed by integrating Augmented Reality (AR) technology. The incorporation of AR in collaborative contexts is considered to foster students' motivation and engagement (Amores-Valencia et al., 2022; Yegorina et al., 2021), while simultaneously strengthening the visual-exploratory elements crucial in spatial learning.

The resulting module was validated by three experts: (1) a mathematics subject-matter expert, (2) a digital pedagogy specialist, and (3) an experienced secondary mathematics teacher. The validation process followed content validity principles (Widoyoko, 2020), recording a mean feasibility score of 92.18%, thereby categorised as *highly valid*. The validation instrument measured five key aspects: (a) alignment of content with numeracy competencies and local ethnomathematical context (Muliana et al., 2023), (b) integration of SRL principles within the learning sequence (Zimmerman, 2002; Wang & Sperling, 2020), (c) effectiveness and usability of collaborative AR design (Schutera et al., 2021), (d) clarity of narration and readability of content, and (e) modular structure supporting students' independent reflection (Ansari et al., 2021; Wiedbusch et al., 2021). The results confirmed that the ME-CAR module complies with the required standards of content relevance, contextual cultural integration, and pedagogical feasibility before field testing. The resulting Ethnomathematics-Collaborative Augmented Reality (ME-CAR) module prototype developed in this study can be accessed at the following link: https://shorturl.at/hr1CT

Figure 6. Product Development

The validation results presented in Table 2 indicate that the ME–CAR module attained an average score within the "highly valid" category across all evaluation dimensions. Qualitatively, the experts provided positive feedback on the module's success in integrating a contextual approach with immersive technology support to foster student engagement and strengthen self-regulated learning. These findings signify that ME–CAR meets academic, pedagogical, and technological standards and is considered relevant to the demands of 21st-century learning, particularly in developing numeracy literacy grounded in local culture and enhancing students' autonomous learning capacity (Geiger et al., 2015; OECD, 2023; Wang & Sperling, 2020). The ethnomathematical approach embedded in the module reinforces prior studies, which emphasize that connecting learning to local cultural contexts can improve the meaningfulness of instruction and students' contextual numeracy (Afgani & Paradesa, 2021; Pratama & Yelken, 2024; Kusuma et al., 2024). Moreover, the incorporation of Augmented Reality (AR) aligns with previous research demonstrating that immersive technologies enhance student engagement, motivation, and learning outcomes (Amores-Valencia et al., 2022; Ziden et al., 2022; Nindiasari et al., 2024). Finally, the module's design to strengthen self-regulated learning strategies is supported by Zimmerman's (2002) framework and empirical evidence from Wang and Sperling (2020) and Ansari et al. (2021), confirming that the development of students' self-regulatory skills plays a crucial role in improving mathematical literacy achievement.

Table 2. Evaluation Results from Subject Matter Experts, Learning Model Experts, and Mathematics Teachers

Evaluators	Indicator	Evaluation Score	Interpretation
Subject Matter Expert	Relevance and Appropriateness of Content	92.12%	Highly Valid
	Appropriateness of Content Presentation	91.09%	Highly Valid
	Contextual Assessment	93.13%	Highly Valid
	Average	92.11%	Highly Valid
Learning Model Expert	Relevance and Appropriateness of Learning Content	95.17%	Highly Valid
	Appropriateness of Model Presentation	89.39%	Highly Valid
	Assessment of Model Implementation	92.14%	Highly Valid
	Average	92.22%	Highly Valid
Mathematics Teacher	Structural Suitability of Flat Shapes Material	92.22%	Highly Valid
	Appropriateness of Language Use and Model Application	90.20%	Highly Valid
	Contextual Assessment Based on Difficulty Level	88.25%	Highly Valid
	Average	90.22%	Highly Valid

Implementation

The implementation of the ME–CAR module was carried out in a phased manner, adhering to the principles of Educational Design Research (EDR). The process consisted of three key stages: a small group trial, a large-scale implementation, and a comparative trial involving a control group. These phases were strategically designed to examine the module's effectiveness, practicality, and implementation impact.

Small Group Trial

The small group trial served as the preliminary stage, aiming to evaluate the initial effectiveness of the ME–CAR instructional design in enhancing students' functional numeracy and self-regulated learning (SRL) abilities. The pre-test results revealed a low baseline average score of 37.00, indicating limited mastery of fundamental mathematical concepts. Following the intervention using the ME–CAR module, the post-test average rose significantly to 87.70. A paired-sample t-test analysis demonstrated a statistically significant difference between the pre- and post-test scores ($t(19) = 11.84, p < 0.001$), with a large effect size (Cohen's $d = 2.12$), suggesting a strong positive impact of the module. This substantial improvement aligns with OECD (2023) findings, which emphasize that 21st-century numeracy competencies are greatly influenced by contextual and visual-based instructional strategies. Furthermore, the correlation between pre- and post-test scores was statistically significant ($r = 0.73, p = 0.016$), indicating consistent learning gains among participants. This is consistent with the assertion of Ansari et al. (2021) that self-regulated learning plays a pivotal role in fostering higher-order mathematical thinking through effective autonomous learning strategies. In addition to quantitative assessment, a student perception survey was conducted, covering 20 quality indicators of the ME–CAR module. The results reflected a highly positive response, with an average rating of 91.26%, categorized as "excellent." This supports previous findings by Amores-Valencia et al. (2022) and Ziden et al. (2022), which confirm the positive impact of interactive technology-based media, such as Augmented Reality (AR), on students' motivation and achievement in mathematics learning.

Table 2. Paired Sample T-Test Results

Pretest Mean	Posttest Mean	t-value	df	Sig. (2-tailed)	Cohen's d	N
37.00	87.70	11.84	19	0.000	2.12	20

Table 3. Small-Scale Trial Results

No	Assessment Indicator	Score Percentage	Interpretation
1	Content Appropriateness	93.13%	Excellent
2	Presentation Quality	90.50%	Excellent
3	Contextual Relevance	92.15%	Excellent
4	Content Consistency	91.19%	Excellent
5	Learning Model Presentation	90.20%	Excellent
6	Usefulness of the Learning Model	91.25%	Excellent
7	Media Compatibility and Ease of Use	90.30%	Excellent
8	Language Appropriateness	92.50%	Excellent
9	Media Contextualization	90.20%	Excellent
	Average	**91.26%**	**Excellent**

Findings from the small group trial revealed an average student perception score of 91.26%, indicating a highly positive response toward the ME-CAR module in terms of content quality, presentation, contextual relevance, and the integration of Augmented Reality (AR) technology. This suggests that the module effectively aligns with the demands of 21st-century education, which emphasizes the integration of local culture, digital technology, and self-regulated learning strategies (Zimmerman, 2002; Wang & Sperling, 2020). These results corroborate systematic reviews by Amores-Valencia et al. (2022) and Ziden et al. (2022), which demonstrated the potential of AR technologies to enhance students' motivation and academic performance in mathematics and science education. Furthermore, the incorporation of self-regulated learning (SRL) principles within the ME-CAR module contributed significantly to the improvement of students' numeracy literacy. This is consistent with findings from Ansari et al. (2021), who argued that learning strategies fostering autonomy and self-regulation significantly enhance higher-order thinking skills in mathematics. The culturally grounded instructional approach adopted in the module also aligns with the PISA framework, which emphasizes the integration of authentic contexts to strengthen mathematical literacy (OECD, 2023; Afgani & Paradesa, 2021). Overall, the small-scale trial provides preliminary evidence that the ME-CAR module is effective in enhancing students' numeracy outcomes while also being positively received in terms of affective engagement. Nevertheless, these findings remain exploratory and warrant further validation through larger and more diverse samples to establish external validity and the generalizability of results (Brenner, 2022; Wiedbusch et al., 2021).

Figure 7. Small Group Trial

ME–CAR Module Practicality Test in a Large-Scale Trial

The subsequent large-scale trial involved 35 students in an authentic classroom setting. The results of the pre-test indicated a mean score of 36.00, while the post-test reached an average of 87.68. A paired sample *t*-test revealed a statistically significant difference ($t(34) = 14.21, p < 0.001$), with a Cohen's d value of 2.15, which falls within the "very large" effect size category. This result indicates a substantial impact of the ME–CAR module on students' numeracy improvement. These findings align with Afgani and Paradesa (2021), who emphasized that integrating ethnomathematical contexts enhances students' relevance and understanding of mathematical problems within real-life settings. Furthermore, OECD (2023) reported that embedding local cultural contexts and digital technologies in mathematics instruction positively influences students' numeracy performance across countries. The assumption of normality was verified using the Shapiro–Wilk test, which confirmed that the data were normally distributed ($p > 0.05$). Additionally, these outcomes are consistent with the findings of Ziden et al. (2022), who demonstrated that Augmented Reality (AR) significantly enhances students' learning outcomes and motivation by providing immersive and contextualized learning experiences. In this regard, the ME–CAR module functions not merely as a visual aid but as a comprehensive numerical exploration tool that empowers students to develop problem-solving abilities, visual interpretation skills, and self-regulated learning competencies.

Table 4. Summary of Statistical Analysis on the Effectiveness of the ME–CAR Module

No.	Statistical Analysis	Result
1	Mean Pretest Score (Indicates low initial numeracy ability)	36.00 (SD = 7.65; N = 35)
2	Mean Posttest Score (Indicates significant improvement in numeracy)	87.68 (SD = 9.21; N = 35)
3	Paired Sample t-test (Indicates statistically significant difference)	t(34) = 14.21; p < 0.001
4	Effect Size (Cohen's d) (Very large effect size)	d = 2.15
5	Normality Test (Shapiro–Wilk) (Indicates normal distribution of data)	Pretest: p = 0.456; Posttest: p = 0.612
6	Reliability (Cronbach's α) (Indicates very high internal consistency)	α = 0.89 (for the practicality instrument, 9 items)

Table 5. Results of Large-Scale Trial Evaluation

No.	Evaluation Indicator	Percentage	Interpretation
1	Content Appropriateness	94.15%	Excellent
2	Contextual Presentation	92.75%	Excellent
3	Cultural Relevance	91.20%	Excellent
4	Visual and AR Design	92.50%	Excellent
5	SRL Strategy Integration	90.50%	Excellent
6	Collaborative Activities	90.60%	Excellent
7	Language and Accessibility	93.00%	Excellent
8	Ease of Implementation	91.20%	Excellent
	Average Practicality Score	**92.01%**	**Excellent**

The practicality of the module was evaluated using eight indicators encompassing pedagogical, technological, and contextual dimensions. The overall mean score reached 92.01%, categorized as *excellent*, supported by a high level of internal reliability (Cronbach's Alpha = 0.89). These findings align with the argument of Wang and Sperling (2020), who emphasized that the success of self-regulated learning is strongly influenced by the availability of instructional media that support visual exploration and student learning autonomy. Content validation was conducted by experts in mathematics education and instructional technology, confirming that the developed module is not only content-valid but also pedagogically practical and contextually relevant for 21st-century learning environments.

Experimental Trial with a Control Group (Comparative Approach)

To rigorously examine the effectiveness of the intervention, a quasi-experimental pretest–posttest design with a control group was conducted. The experimental group received instruction using the ME–CAR module, whereas the control group was taught using a conventional approach without the module. Initial differences in pretest scores were identified, necessitating the use of Analysis of Covariance (ANCOVA) to statistically control for baseline disparities. Descriptive analysis revealed a substantial improvement in the experimental group's scores from 36.00 to 87.68 (see Table 6), while the control group showed an increase from 34.88 to 62.00 (see Table 7). ANCOVA results indicated a statistically significant difference between the two groups after controlling for pretest scores, $F(1,67) = 18.21, p < 0.001$, with a partial eta squared value of 0.214, suggesting a large effect size. The assumptions of normality (Shapiro–Wilk, $p > 0.05$) and homogeneity of variances (Levene's test, $p = 0.292$) were met, confirming the validity of the ANCOVA analysis. Adjusted posttest means further demonstrated that the experimental group achieved a higher score ($M = 86.72$) than the control group ($M = 63.14$) (see Table 8). The calculated Cohen's d effect size of 2.15 indicates a very large impact of the ME–CAR module on students' numeracy improvement.

These findings are consistent with Wang and Sperling (2020), who found that technology-integrated self-regulated learning (SRL) interventions significantly enhance students' engagement and mathematics achievement. Moreover, studies by Amores-Valencia et al. (2022) and Ziden et al. (2022) confirmed that Augmented Reality (AR) applications substantially improve learning motivation and the comprehension of abstract mathematical concepts, including spatial geometry visualization. Furthermore, research by Afgani and Paradesa (2021) highlights that embedding ethnomathematical contexts not only fosters numeracy but also enhances students' cognitive engagement and cultural connectedness in learning. Hence, the effectiveness of the ME–CAR module is not solely evident in quantitative metrics, but also reflects its pedagogical value as a culturally responsive, reflective, and technologically enriched approach to mathematics instruction. Nevertheless, the generalizability of these findings remains limited due to the restricted geographic and institutional scope of the study, as echoed in OECD (2023), which calls for broader cross-context and demographic validation of numeracy instruments and instructional models.

Table 6. Descriptive Statistics of Pretest and Posttest Scores

Group	N	Pretest Mean (SD)	Posttest Mean (SD)
Experimental	35	36.00 (5.12)	87.68 (4.75)
Control	34	34.88 (4.93)	62.00 (5.29)

Table 7. ANCOVA Results of Numeracy Posttest Scores After Controlling for Pretest

Source	df	Mean Square	F	Sig.	Partial Eta²
Pretest (Covariate)	1	72.13	3.31	0.073	0.047
Group	1	9854.44	18.21	0.000	0.214
Error	67	541.86			

Table 8. Adjusted Mean of Numeracy Posttest Scores Based on ANCOVA

Group	Adjusted Mean	Standard Error	95% CI (Lower)	95% CI (Upper)
Experimental	86.72	1.12	84.49	88.94
Control	63.14	1.15	60.85	65.43

The findings further substantiate the effectiveness of the developed module, which had previously demonstrated both conceptual and practical validity, particularly in enhancing students' cognitive engagement. The module has successfully fostered the use of key learning strategies such as self-regulation and collaboration, critical components in the development of higher-order thinking skills (Ansari et al., 2021; Wang & Sperling, 2020). Moreover, the integration of culturally contextualized content has positively influenced students' mathematical motivation and literacy (Tanujaya et al., 2021; Afgani & Paradesa, 2021). The incorporation of visual-spatial and reflective dimensions also played a pivotal role in promoting deep metacognitive engagement (Wiedbusch et al., 2021; Zimmerman, 2002). Nevertheless, it is important to note that the current study did not involve a control group, which may introduce potential bias in interpreting the outcomes. Therefore, future studies employing more rigorous experimental designs, such as the pretest–posttest control group design, are strongly recommended to confirm the module's effectiveness more comprehensively (Brenner, 2022; OECD, 2023).

Evaluation

Evaluation was carried out through two main approaches: expert validation and field implementation (limited and large-scale trials). Content validation involved three key stakeholders: subject matter experts, pedagogy experts, and practicing teachers, in line with the principles of formative evaluation in Educational Design Research (Plomp & Nieveen, 2013). The evaluation focused on aspects of practicality and effectiveness, responding to the needs analysis findings that indicated low student achievement and limited engagement in learning three-dimensional geometry. This aligns with the OECD (2023) report, which highlights the influence of instructional strategies and contextual media on numeracy literacy. The validation results were highly positive, with scores of 92.11% (subject matter experts), 92.22% (pedagogy experts), and 90.22% (practicing teachers), confirming the fulfillment of content validity, pedagogical appropriateness, and instructional applicability standards. These findings are consistent with Ansari et al. (2021) and Amores-Valencia et al. (2022), who emphasized the importance of integrating instructional strategies with contextual digital media to foster higher-order thinking skills and student learning autonomy. At the implementation stage, trials using pre-tests, post-tests, and practicality questionnaires demonstrated significant improvement: students' average scores increased from 37 (pre-test) to 87.7 (post-test). The practicality score reached 91.26%, confirming high readability, engagement, and ease of use. These results are in line with Wang and Sperling (2020), who stressed that the effectiveness of learning media depends on its ability to stimulate students' self-regulation in mathematics learning.

In the large-scale field trial, a consistent evaluation pattern was employed. The mean score of the students' pre-test was 36, which significantly increased to 87.68 in the post-test. A comprehensive assessment of the teaching module by students resulted in an average score of 92.01%, indicating the consistent quality and applicability of the module in broader classroom contexts. These results demonstrate that the developed instructional module is not only valid in terms of content and practicality but also effective in enhancing students' learning outcomes. The quantitative evaluation was reinforced by qualitative findings, revealing that students found the instructional module helpful in meaningfully and collaboratively understanding the topic of plane geometry. This highlights the crucial role of well-structured learning media in promoting active engagement and self-directed learning strategies. In this regard, the self-regulated learning (SRL) approach has been shown to contribute significantly to improved academic achievement (Wang & Sperling, 2020; Zimmerman, 2002; Ansari et al., 2021). The module also fosters reflective activities and intrinsic student motivation, in alignment with the principles of autonomy-supportive and self-regulated instruction (Brenner, 2022). Based on these empirical findings and the design-based evaluation approach, it can be concluded that the developed instructional module is a viable pedagogical tool to support students' competency development optimally and sustainably.

Discussion

The effectiveness of the instructional module is supported by two main indicators. First, the average post-test score of students in the experimental group reached 87.68, well above the minimum mastery criteria (MMC) of 75, indicating that students were able to comprehend the learning materials effectively through the use of the module. This finding aligns with Emanet & Kezer (2021), who noted that student-centered modular instruction significantly improves academic performance and fosters positive attitudes toward mathematics. Second, the module's effectiveness is further substantiated by the performance gap between the experimental group (mean $=$ 87.68) and the control group (mean $=$ 62), showing a substantial difference of 25.68 points. If statistical testing (e.g., paired-sample t-test) confirms this difference as significant ($p < 0.05$), it provides strong empirical evidence that the module exerts a meaningful impact on learning outcomes. This conclusion is supported by Ziden et al. (2022) and Wang & Sperling (2020), who emphasize that innovative learning materials that integrate technology and self-regulated learning strategies can enhance student motivation, autonomy, and achievement in mathematics. Hence, the use of this instructional module is demonstrably effective in significantly improving students' learning outcomes on the topic of plane geometry.

The development of the instructional module on *plane solid geometry* in this study was carefully designed concerning essential quality indicators, including content feasibility, clarity and coherence of material presentation, appropriateness of the implemented learning model, integration of technology and instructional media, use of communicative language, and contextual relevance to students' real-life experiences (Muliana et al., 2023; Ramadhan et al., 2024). Validation by subject matter experts, pedagogical model experts, and educational technology experts confirmed the module's high quality, as reflected in the average expert scores, which fell within the "excellent" category (Emanet & Kezer, 2021; Diamah et al., 2022).

The module also emphasizes the implementation of a cooperative learning model augmented with immersive technology to foster student interaction, enhance visualization, and strengthen students' self-regulated learning (Zimmerman, 2002; Nindiasari et al., 2024). Empirical evidence supports the effectiveness of cooperative learning in improving students' social and academic engagement, encouraging collaboration, and deepening conceptual understanding through group discussions (Ansari et al., 2021; Zhou et al., 2025). The implementation of technology-assisted cooperative modules led to a significant improvement in students' learning outcomes, as evidenced by statistical differences between pretest and posttest scores in the experimental class (OECD, 2023; Yulianto et al., 2025). This approach also aligns with the objectives of 21st-century mathematical literacy and the competencies outlined in the Indonesian National Assessment (AKM) framework (Geiger et al., 2015; Ministry of Education and Culture, 2020).

The use of the ME-CAR module (Ethnomathematics–Collaborative Augmented Reality) in this study demonstrated a positive impact on students' understanding and learning achievements in culturally integrated *plane solid geometry* rooted in Baduy traditions. The module offers a flexible, interactive, and visually rich learning experience, thereby supporting the development of students' self-regulated learning and academic independence (Zimmerman, 2002; Wang & Sperling, 2020; Ansari et al., 2021). The integration of cooperative strategies within an ethnomathematical, technology-enhanced module represents an innovative instructional practice that is highly relevant to enhancing 21st-century mathematical literacy (OECD, 2023; Geiger et al., 2015; Yulianto et al., 2024). This finding is consistent with previous research highlighting the importance of selecting appropriate digital learning media to improve student motivation and academic performance (Amores-Valencia et al., 2022; Ziden et al., 2022; Nindiasari et al., 2024). Validity, practicality, and effectiveness tests showed a significant increase in posttest scores compared to pretest scores, further validating the meaningful impact of augmented reality–based and culturally integrated instructional modules on student learning outcomes (Ishartono et al., 2022; Batiibwe, 2024; Muliana et al., 2023). Accordingly, this study contributes new empirical insights into the integration of ME-CAR technology and cooperative learning approaches in ethnomathematics instruction to optimize both mathematical literacy and students' self-directed learning capacity.

Implications

The findings of this study suggest that integrating technology-based instructional modules with cooperative learning approaches can significantly enhance the quality of mathematics instruction. Teachers are encouraged to utilize these insights to enrich their teaching strategies, particularly when delivering abstract mathematical concepts such as plane geometry, which often pose challenges for students. Nevertheless, this study is constrained by several limitations that should be acknowledged for greater transparency. First, the research sample was relatively limited and drawn from a specific educational setting, which may restrict the generalizability of the findings to broader populations. Second, the study primarily focused on one mathematical topic, plane geometry with flat surfaces, and therefore does not capture the potential variation of the module's effectiveness when applied to other mathematical domains. Third, the evaluation relied heavily on pre-test and post-test instruments, supported by questionnaires, which, while robust, may not fully capture the depth of students' long-term retention and transfer of knowledge. In addition, although the ME-CAR module integrates ethnomathematical and technological elements, cultural representation was limited to the Baduy context, and thus, further studies are needed to examine its adaptability to other cultural traditions. Based on these limitations, caution is warranted in generalizing the findings, and further research is recommended to examine the effectiveness of the ME-CAR module across diverse mathematical topics, educational levels, and cultural contexts. Longitudinal studies would also be valuable to investigate the sustainability of its impact on students' mathematical literacy and self-regulated learning.

CONCLUSION AND SUGGESTIONS

Based on the development process, expert validation, and limited field trials, the Ethnomathematics–Collaborative Augmented Reality (ME-CAR) module has proven to be both feasible and effective in enhancing students' functional numeracy and self-regulated learning (SRL) capabilities in a meaningful way. The integration of local ethnomathematical contexts, augmented reality technology, and collaborative learning strategies has resulted in an immersive, reflective, and cognitively engaging learning experience. The findings affirm that culturally grounded and technology-enhanced instructional design can serve as a strategic approach to improving the quality of 21st-century mathematics education at the secondary level.

Mathematics teachers are encouraged to utilize the ME-CAR module as part of innovative, context-based instructional practices to foster students' numeracy and independent learning skills through collaborative, technology-mediated activities. School administrators and policymakers are advised to support the provision of infrastructure, teacher training, and policy development that embraces ethnomathematics-based technology integration to enable the broader implementation of this innovative learning resource. Future research is recommended to broaden the sample coverage across diverse school contexts, examine the impact of the ME-CAR module on other higher-order thinking skills (such as critical thinking, problem-solving, and creativity), and explore the integration of artificial intelligence to enhance the module's adaptability to students' individual learning needs. Further research is recommended to explore the effectiveness of the ME-CAR module across diverse mathematical topics, different school contexts, and broader cultural traditions. In addition, longitudinal studies are needed to examine the sustainability of its impact on students' mathematical literacy and self-regulated learning.

Practical Recommendations for Teachers/Educators. Teachers are advised to integrate technology-based and culturally contextualized instructional modules, such as ME-CAR, to make abstract mathematical concepts more concrete and engaging. Incorporating cooperative learning strategies within digital modules can enhance collaboration, peer learning, and self-regulated learning. Teachers are also encouraged to adapt ethnomathematical elements from their local cultures to increase relevance and student motivation. Moreover, the use of reflective activities within the module can support students in developing autonomy, critical thinking, and long-term retention of concepts.

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