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PAPER

From Novelty to Pedagogy: The CORE-MR Framework for Mobile Mixed Reality in Elementary Mathematics

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ABSTRACT

Mixed reality (MR) in mathematics education offers the potential to make abstract concepts more concrete and engaging. However, a gap persists between the technological design of MR tools and the complex realities of classroom instruction. This research is urgent because limited studies explain *how* MR learning designs evolve and support student understanding in practice. Participants included 300 elementary students and 100 teachers in multiple school settings, while a purposive sub-sample of 30 students was selected for in-depth qualitative analysis. The study employed didactical design research (DDR), consisting of prospective, metadidactic, and retrospective stages. Data were collected through classroom observations, semi-structured interviews, and student digital artifacts. Data analysis was conducted using thematic analysis. The findings indicate that MR effectively strengthens spatial reasoning and conceptual understanding of 3D geometry, though some students experienced initial cognitive overload and difficulty transferring visual understanding to symbolic mathematical representations. The implementation also required teachers to shift toward facilitative orchestration of learning activities. The study concludes that DDR enables iterative refinement of MR-based learning designs to better align with authentic classroom needs. This research contributes practical design principles for developing pedagogically grounded MR learning environments.

KEYWORDS

didactical design research (DDR), elementary students, geometry learning, Mathematics Learning, mixed reality (MR)

1 INTRODUCTION

Mixed reality (MR) in education is widely presented as a promising approach for supporting learning through immersive and embodied interaction [1]. However, current classroom research shows a recurring gap between the technical design of MR tools and the practical, socially situated demands of instruction. Empirical MR research in mobile learning contexts shows that although immersive designs can improve learning outcomes and engagement, the instructional processes through

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which these effects are produced are often insufficiently specified [2]. This gap is not only an implementation issue but reflects a limited understanding of how MR-based learning processes develop during classroom use. While multiple studies report positive effects of MR on student engagement and learning outcomes [3]–[8], they rarely describe the mechanisms through which these outcomes emerge or fail to emerge. As a result, MR interventions are often reported as finished products, while the evolution of their learning designs remains insufficiently documented.

This situation persists because many studies operate within a paradigm that prioritizes summative evaluation rather than formative and theory-building design work [9], [10]. The dominant research question has been, "Is MR effective?" rather than, "How should MR learning be designed, and what theoretical principles guide that design process?" When MR applications do not achieve the intended learning goals, the resulting analyses tend to remain descriptive. For example, Fjærestad and Xenofontos (2025) note that students became absorbed in game mechanics at the expense of mathematical ideas [11], yet findings of this kind are rarely translated into design knowledge that can inform future development.

To address this gap, the present study adopts didactic design research (DDR) as its methodological approach. DDR provides a structured process for linking theoretical assumptions, design decisions, and empirical classroom observations [12], [13]. Rather than treating development as a linear build-and-test cycle, DDR examines a hypothetical learning trajectory (HLT), its enactment in authentic instruction, and the empirical adjustments that follow. In this framework, the classroom serves not merely as a testing environment but as a context in which design assumptions are validated, challenged, and refined [14]. This methodological orientation directly responds to calls for more integrated and theory-informed pedagogical frameworks in mobile learning research [15]. The aim is not only to produce a functioning MR tool but also to contribute what Gravemeijer and Cobb (2013) refer to as "local instruction theories" context specific explanations of why a design works, under which conditions, and how it can be adapted [16], [17].

This paper reports a DDR study focused on an MR platform for elementary mathematics. The contribution of the study is twofold: (1) it generates empirically informed design principles for MR-based mathematics learning, and (2) it demonstrates how DDR can produce actionable insight into the interaction between immersive technology, pedagogical design, and student thinking. The study is guided by the following research questions:

- What is the initial didactical design for the MR mathematics platform, and what theoretical and pedagogical assumptions underpin this HLT?
- How is the initial HLT realized and perceived in practice, and what divergences emerge between the anticipated and actual student learning processes and experiences?
- Based on the empirical findings from implementation, what specific improvements and iterative refinements can be made to the didactical design of the MR platform to better support mathematics learning?

2 LITERATURE REVIEW

2.1 Mixed reality as a pedagogical tool

Scholars define MR as existing on the spectrum between augmented reality (AR) and virtual reality (VR) [18] and highlight its potential to generate engagement and create hands-on learning experiences with abstract subject matter [19]. The documented advantages of AR include increased intrinsic motivation [20], greater engagement with multimedia content [21], and the facilitation of interactive worksheets [22]. Parallel to this, VR has been recognized for its utility in incorporating indigenous cultural contexts [23], enhancing spatial abilities via mobile apps [24], and enabling lab-simulated activities in the classroom [25]. In contrast, MR studies in elementary mathematics remain limited.

In education, MR moves beyond the passive viewing of VR or the screen-bound limitations of AR, enabling students to manipulate virtual objects as if they were physically present, creating a hybrid environment where physical [26], [27] and digital objects co-exist and interact in real-time [28]. This capability is particularly potent in mathematics education, where abstract concepts like geometric shapes, spatial relationships, and volume can be transformed into tangible, interactive experiences. For students who often benefit from concrete operational stages, this direct manipulation fosters deeper conceptual understanding and retention compared to traditional two-dimensional representations [29]. Theoretically, this aligns with embodied cognition, suggesting that physical interaction with mathematical concepts can ground abstract thinking in sensory-motor experiences [30]. Furthermore, MR can provide immediate feedback and adaptive challenges, supporting personalized learning paths that cater to individual student needs and pacing.

2.2 The platform: Integrated MR learning architecture

The specific mixed reality platform developed in this study serves as the technological core of the research. It was designed with a dual-component architecture to ensure both immersive exploration and structured learning. The system consists of (1) a web-based course hub built on a responsive learning management system (LMS) for delivering structured content, tracking student progress, and hosting interactive quizzes; and (2) an Android-based MR application that enables immersive manipulation of 3D geometric solids (e.g., cube, cuboid, cone, cylinder, pyramid, and sphere) through rotation, scaling, and virtual dissection.

This integrated design aims to bridge direct digital instruction with hands-on spatial reasoning. Prior to implementation, the platform underwent expert validation, which confirmed high feasibility with content validity indices of 87.50% for material and 83.33% for media, indicating strong alignment with curriculum standards and interface usability.

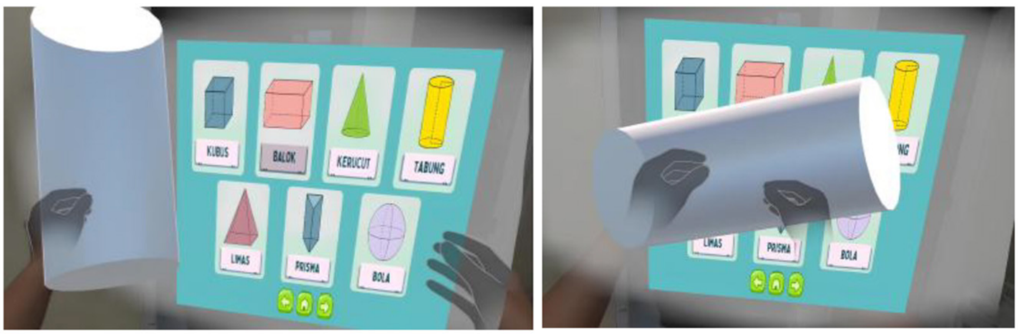

Fig. 1. MR application

Figure 1 illustrates the 3D Shapes feature, one of the primary mixed reality interaction modes, in which geometric solids are rendered as manipulable objects within the learner's field of view. Through direct hand-based gestures such as rotation, zooming (scaling), and spatial translation, students can examine virtual shapes without menu navigation or button inputs. This gesture-driven modality supports spatial reasoning by enabling embodied inspection from varied perspectives, distances, and positions.

2.3 Didactical design research (DDR): A framework for bridging theory and practice

To bridge the gap between the MR platform's potential and its effective classroom application, this study is grounded in the methodology of didactical design research (DDR). DDR is a research approach that focuses on the design process to develop learning experiences that solve complex educational problems [31]. This study specifically adopts the three-stage DDR model articulated by Suryadi (2013), which provides a structured framework for iterative development [32]. The stages are illustrated in Figure 2 and elaborated below:

Fig. 2. Stages of DDR

Prospective analysis is the initial design stage, where the researcher constructs a detailed analysis of the didactic situation [33]. This involves designing an HLT that students are expected to follow [34]. Metadidactie analysis is the empirical stage of implementation and observation [35]. The designed HLT is enacted in a real classroom setting. Here, the researcher systematically collects data to analyze the obstacles and challenges students face when interacting with the learning trajectory. Retrospective Analysis is the stage of reflection and redesign. The researcher connects the findings from the metadidactic analysis with the initial prospective analysis. The discrepancies between the anticipated and actual learning processes become the basis for creating a revised didactic design [36].

3 METHOD

3.1 Research design

This study employed a qualitative approach within the framework of DDR using the three-stage model proposed by Suryadi (2013): prospective analysis, metadidactic analysis, and retrospective analysis [32]. This design was selected because it provides a systematic, iterative process for developing and refining educational interventions based on empirical evidence from real-world classroom settings. The primary goal was not merely to evaluate the final MR platform but to understand and document the process of its development, focusing on the interplay between the designed learning trajectory (HLT) and the actual experiences of students and teachers.

3.2 Participants

This study employed a two-stage sampling strategy to ensure both broad implementation and depth of qualitative insight. First, the MR platform was implemented with a cohort of 300 elementary students and 100 teachers across six public elementary schools in Cirebon Regency (refer to Table 1). These schools were selected purposively based on adequate digital infrastructure, device availability, and teacher readiness, allowing the MR platform to be tested in varied yet realistic classroom conditions.

Table 1. Distribution of implementation participants across schools

School Code	Students Participating	Teachers Participating	Notes
SD-1	43	15	Adequate digital readiness
SD-2	41	14	Strong teacher ICT integration
SD-3	48	17	Stable internet, active LMS usage
SD-4	50	18	Consistent class schedule
SD-5	51	17	Good device availability
SD-6	67	19	Largest implementation cohort
Total	**300 students**	**100 teachers**	

In alignment with the qualitative orientation of DDR, the analytic dataset focused on a purposive subsample of 30 students with varied ability levels and learning experiences and 15 teachers offering diverse pedagogical perspectives. This sub-sample enabled detailed examination of learning processes, didactical interactions, and emerging obstacles during the MR implementation. All participants were informed about research procedures, parental consent was secured, and confidentiality was maintained. Ethical clearance was granted by the Institute for Research and Community Service (LPPM) of the Prima Bangsa Institute on June 7, 2025.

Table 2. Student interaction metrics during MR implementation

Metric	Description	Value
Unique Logins	Total distinct students accessing the platform	300 students
Total Login Events	Total login occurrences across implementation	1,226 logins
Average Logins per Student	Frequency of access per student	4.4 times
Average Session Duration	Mean platform usage time per session	19 minutes
Average Object Rotations	Mean rotation gestures per session	22 times
Average Object Translations	Mean horizontal/vertical moves per session	15 times
Average Zoom Gestures	Mean scaling (zoom in/out) gestures per session	11 times
Module Completion Rate	Students completing all accessed modules	91%
Assessment Attempt Rate	Students attempting built-in quizzes	86%

The metrics in Table 2 indicate that learners engaged with the platform in sustained and iterative ways rather than brief exploratory usage. Repeated access and non-trivial session lengths suggest that the MR environment functioned as an instructional space rather than a novelty. Gesture patterns imply that the 3D objects were actively manipulated, supporting embodied inspection rather than passive viewing. High module completion and assessment attempt rates further show that most learners progressed through structured tasks to evaluative components. Collectively, these patterns reflect coherent engagement aligned with instructional objectives and provide sufficient interaction density for subsequent didactical analysis.

3.3 Data collection and analysis

Data was collected during the Metadidactic analysis stage to capture the implementation of the HLT. To ensure comprehensive triangulation, multiple qualitative data sources were utilized, as detailed in Table 3.

Table 3. Data collection methods and instruments

Data Source	Instrument	Participants
In-depth Interviews	Semi-structured interview protocols (separate for students and teachers).	Students (n = 30): A purposive sub-sample from the implementation.
		Teachers (n = 15): A purposive sub-sample of the involved teachers.
Student Artifacts	The MR platform's screenshot function and manual screen recording.	Students (n = 300): The broader implementation cohort was encouraged to save their work.
Non-participant observation	Structured observation sheet focusing on student-teacher-media interaction, collaboration, and usability.	Students and teachers in the classroom setting during implementation.

The qualitative data from interviews and observations were analyzed using thematic analysis following the approach of Braun and Clarke (2006) [37]. The process involved: (1) Transcribing interviews and organizing observation notes and artifacts; (2) Generating initial codes from the diverse data sets; (3) Searching for themes based on the codes, specifically looking for patterns related to the alignment or divergence from the HLT; and (4) Reviewing and defining themes, which were then used to inform the retrospective analysis and the redesign of the HLT.

3.4 Validity and reliability

To ensure the trustworthiness of this qualitative study, several strategies were employed, as suggested by Lincoln and Guba (1985) [38]: Credibility was ensured through triangulation of multiple data sources, including student interviews, teacher interviews, classroom observations, and student artifacts, complemented by member checking, in which preliminary interpretations were reviewed by participating teachers. Transferability was supported by providing thick, contextual descriptions of the research setting, participant characteristics, and implementation procedures, further strengthened by the scale of the implementation cohort (300 students and 100 teachers) and the depth of qualitative sampling. Dependability was maintained through a detailed audit trail documenting research decisions and iterative steps across the DDR cycles, ensuring that the research process remained systematic and traceable. Confirmability was upheld through ongoing researcher reflexivity, whereby potential biases and interpretive influences were continually examined to safeguard the objectivity of the findings.

4 RESULTS

This section presents the findings of DDR, structured according to its three core stages: the Prospective Analysis (initial design), the Metadidactic Analysis (implementation), and the Retrospective Analysis (redesign).

4.1 Prospective analysis: The initial didactic design for learning (addressing RQ1)

The HLT is a structured set of conjectures about a possible path of learning, formulated based on an analysis of the learning objectives, anticipated learning obstacles, and a designed sequence of activities intended to overcome those obstacles. The core components of the HLT are summarized in Table 4.

Table 4. The HLT conjectures

Learning Phase	Learning Objective	Anticipated Learning Obstacles	HLT Conjecture & Designed Activity
Definitions and Types	Students can understand definitions and identify various types of 3D shapes.	Students struggle to differentiate between similar shapes based on textual definitions alone.	Conjecture: Interactive MR visualization will help students build accurate mental categorization of 3D shapes.
			Activity: Students explore the "Definition & Types" module, observing 3D models alongside text.
Characteristics	Students can describe and count the characteristics (faces, edges, vertices) of 3D shapes.	Students cannot visualize "invisible" parts and often miscount from a single viewpoint.	Conjecture: MR manipulation will enable systematic observation and accurate counting from all angles.
			Activity: Using the "3D Shapes" feature, students rotate and zoom to count faces, edges, and vertices.
Calculate Surface Area	Students can calculate the surface area of basic 3D shapes.	Students fail to understand that surface area is the total area of all faces and struggle to visualize nets.	Conjecture: MR visualization of shape "unfolding" will help students understand the surface area conceptually.
			Activity: "Surface Explorer" MR feature that shows nets and calculates area step-by-step.
Calculate Volume	Students can calculate the volume of basic 3D shapes.	Students confuse volume with surface area and memorize formulas without understanding space occupation.	Conjecture: MR visualization of "filling" shapes will help students understand volume as internal capacity.
			Activity: "Volume Filler" MR tool that shows virtual filling with unit cubes.
Word Problems (Assessment)	Students can apply all concepts to solve word problems.	Students cannot translate word problems into 3D models and select appropriate solutions.	Conjecture: MR modeling of real-world problems will improve problem-solving abilities.
			Activity: Automated assessment with word problems where students use MR models to visualize and solve.

4.2 Metadidactic analysis: The reality of implementation and emergent divergences (addressing RQ2)

The metadidactic analysis revealed critical divergences between the hypothetical learning trajectory and the observed learning processes, providing empirical answers to the second research question. The analysis, based on triangulated data from interviews and observations, uncovered three primary themes: heightened engagement versus cognitive overload, the struggle for conceptual transfer, and challenges in didactical orchestration.

MR Learning process: A sequential implementation. The five-stage trajectory was constructed as a didactic response to the prospective analysis rather than as a software sequence. The analysis identified three clusters of learning obstacles: (1) epistemological obstacles, namely fragmented linking between 2D and 3D representations; (2) ontogenetic obstacles related to limited spatial visualization; and (3) didactical obstacles in classroom practices where surface area and volume are taught procedurally. Based on these findings, the first stage established a milieu for object classification, functioning as an a priori condition for semantic stabilization before quantitative reasoning. Within the a priori analysis, mental rotation was identified as a key didactical variable affecting students' ability to recognize invariants across viewpoints. Thus, actions such as orientation change were introduced not as technological affordances but as didactic means to anticipate and overcome ontogenetic obstacles.

The second and third stages then addressed the epistemological gap between solids and their nets by manipulating the didactical variable of representation change (3D ↔ 2D) to support the construction of geometric structure. Volume measurement was positioned after surface nets because the prospective analysis revealed systematic conflation between "covering" and "filling." Introducing unit-cube filling served as an embodied operationalization of internal space, separating it from boundary measures. This constituted the core didactical variable for distinguishing volume from surface area. The final contextualization phase constituted the a priori trajectory closure, aimed at observing how students mobilized constructed notions within a problem milieu. In DDR terms, this reflects the transition from prospective to retrospective analysis, where the designed trajectory is confronted with anticipated student responses. This shift from software functionality to didactical justification ensures alignment with the DDR framework, where design decisions emerge from the prospective analysis rather than interface affordances.

Theme 1: Enhanced spatial understanding amidst occasional cognitive overload. The MR platform demonstrated significant effectiveness in developing spatial reasoning, though some students experienced cognitive challenges during the initial adaptation period (see Table 5).

Table 5. Interview results classified into theme 1

Positive student experiences dominated the responses:
• **S15:** *"Ohh, now I get it! A cube really has six faces. When I turned it around in MR, I could finally see and count all the sides, even the ones you can't see in a book."* • **S08:** *"Using MR made the lesson easier. When I spun the pyramid and counted the edges myself, I remembered it better than when I just memorized it from class."* • **S22:** *"I used to think a cone and a cylinder were almost the same. But in MR, when I looked at the shapes from different angles, I could clearly see how they're different."* • **S29:** *"It was fun to move the shapes around by myself. Doing it with my own hands helped me remember what each shape is like."* • **S11:** *"I always mixed up cubes and cuboids. But in MR, I could finally tell which one is which."*
Teachers confirmed these spatial learning benefits:
• **T05:** *"Approximately 70% of students showed improved spatial visualization skills. They could mentally manipulate shapes better after the MR sessions, particularly in Stages 1 and 2."* • **T12:** *"The hands-on manipulation in Stage 2 helped visual learners tremendously. Students who typically struggled with spatial tasks demonstrated marked improvement."* • **T09:** *"The immediate visual feedback when students manipulated shapes provided powerful reinforcement that traditional methods cannot match."*

(Continued)

Table 5. Interview results classified into theme 1 *(Continued)*

Some cognitive challenges were noted by a minority:
• **S03:** *"Sometimes there were too many things to click. I ended up playing with the zoom instead of counting the vertices like I was supposed to."* • **S17:** *"At first I felt a bit confused because there were so many buttons. But after about ten minutes, I got used to it and the learning felt much easier."* • **T07:** *"About 30% of students needed additional guidance to stay focused on the learning objectives rather than exploring all the technological features."*

Theme 2: Strong conceptual foundation with some transfer challenges. The MR platform excelled in building conceptual understanding, though some students needed additional support connecting these concepts to formal mathematical representations (see Table 6).

Table 6. Interview results classified into theme 2

Strong conceptual gains were widely reported:
• **S25:** *"The volume filler finally made me understand volume as the space inside. Before that, I only memorized the formula."* • **S14:** *"The net animation helped me see why we calculate every face. When it unfolded, everything just clicked."* • **S06:** *"The real-world problems were easier because I could picture the objects in 3D. The MR models helped me know what the questions meant."* • **S19:** *"I used to dislike geometry, but MR made it fun. The visuals fit how I learn better than formulas."*
Teachers observed substantial conceptual development:
• **T04:** *"The platform provided exceptional conceptual scaffolding. Students developed a deep understanding of geometric properties that typically takes weeks to build."* • **T11:** *"In Stage 4, the volume visualization helped eliminate the common confusion between surface area and volume. Students could literally see the difference."* • **T15:** *"The progressive sequencing from concrete manipulation to abstract application worked well for building conceptual understanding step by step."*
Some transfer challenges emerged:
• **S09:** *"I understood the concepts in MR, but sometimes struggled to apply them in paper-based tests. The connection between the visual and symbolic needed more practice."* • **S26:** *"When we moved from MR to textbook problems, I missed the interactive visualization. It took time to adjust to static images."* • **T13:** *"While conceptual understanding was strong, we noticed some students became dependent on the visual scaffolding and needed support transitioning to symbolic reasoning."*

Theme 3: High engagement with evolving teaching practices. The MR implementation generated exceptional student engagement while requiring teachers to develop new instructional strategies (see Table 7).

Table 7. Interview results classified into theme 3

Student engagement was overwhelmingly positive:
• **S30:** *"This was the most fun I've ever had learning math. I looked forward to every MR session and even asked to continue during breaks."* • **S05:** *"The MR lessons didn't feel like traditional learning. It was so interactive and engaging that time passed quickly."* • **S18:** *"I usually struggle to pay attention in math class, but with MR, I was completely focused. The immersive experience kept me engaged throughout."* • **S12:** *"Working with MR felt like playing an educational game. I learned without realizing I was learning difficult concepts."*

(Continued)

Table 7. Interview results classified into theme 3 *(Continued)*

Teachers noted the engagement benefits and adaptation needs:
• **T02:** *"Student motivation reached levels I've rarely seen in mathematics classes. Even typically disengaged students participated actively in all five stages."* • **T08:** *"The technology required me to develop new classroom management strategies. I shifted from direct instruction to more facilitative teaching, which ultimately benefited student-centered learning."* • **T10:** *"While initial technical support demands were high, the investment paid off in sustained student engagement and deeper mathematical understanding."* • **T06:** *"The MR environment naturally differentiated instruction – advanced students could explore more complex manipulations while struggling learners received immediate visual feedback."*

4.3 Retrospective analysis: Iterative refinement of the didactical design (addressing RQ3)

Based on the empirical findings from the metadidactic analysis, the initial didactical design was iteratively refined. The retrospective analysis synthesizes these evidence-based revisions, which are structured to address the identified challenges of cognitive load, the representational bridge failure, and pedagogical orchestration. The comprehensive redesign for the next cycle is detailed in Table 8.

Table 8. Revised didactic design: From initial conjecture to evidence-based improvement

Learning Phase	Initial HLT Conjecture & Activity	Key Findings from Implementation	Revised HLT Conjecture & Activity
Definitions and Types	Initial: Unrestricted exploration of all 3D models with definitions.	High initial cognitive load: students are distracted by all features at once.	Revised: Structured & Segmented Exploration.
	Aim: Build foundational knowledge through immersion.		Activity: "Guided Discovery" module. Students explore one shape category at a time (e.g., prisms first). Rotation is enabled but zoom/other effects are locked initially to reduce cognitive load.
Characteristics	Initial: Free manipulation to count faces, edges, and vertices.	Students struggled to systematize counting; manipulation was often aimless.	Revised: Scaffolded Analysis with Explicit Protocol.
	Aim: Hands-on investigation of properties.		Activity: "Characteristic Detective" task. Students use a digital worksheet that guides them to "Find all the faces first," "Now count the edges," etc., while using specific MR tools (e.g., a "highlight edges" button). This adds structure to the exploration.
Calculate Surface Area	Initial: Visualization of shapes unfolding into nets.	The "visualization gap"; students saw the net but didn't connect it to the formula.	Revised: Interactive Formulation.
	Aim: Bridge solid form and abstract calculation.		Activity: "From Net to Formula" activity. The MR platform doesn't just show the net; it allows students to interactively calculate the area of *each face* on the net. The platform then sums these areas automatically, visually demonstrating that the formula is just a shortcut for this total.

(Continued)

Table 8. Revised didactic design: From initial conjecture to evidence-based improvement *(Continued)*

Learning Phase	Initial HLT Conjecture & Activity	Key Findings from Implementation	Revised HLT Conjecture & Activity
Calculate Volume	Initial: "Volume Filler" tool to show space occupation.	Students understood the concept but failed to link the unit cubes to the symbolic formula	Revised: Bridging the Concrete-Abstract Gap.
	Aim: Understand volume as internal capacity.		Activity: "Formula Derivation" challenge. The MR tool is enhanced. After filling a cuboid, it overlays a grid and prompts: "The length is 4 units, width 3 units, height 2 units. How many cubes are in one layer? How many layers?" This guides students to discover and understand the formula rather than just observe the result.
Word Problems (Assessment)	Initial: Use MR models to solve contextual problems.	Students became dependent on the MR scaffold; performance dropped without it.	Revised: Faded Scaffolding Assessment.
			Activity: A multi-step assessment.
	Aim: Apply learning to real-world scenarios		Part 1: Solve a problem with full MR support.
			Part 2: Solve a similar problem with a static 3D image from the MR.
			Part 3: Solve a problem with only a diagram. This design explicitly trains and assesses the ability to transfer understanding away from the immersive tool.

The revised didactical design is governed by three core principles derived from the DDR process:

1. Principle of Managed Cognitive Load: Immersive learning must be scaffolded. The sequence should move from limited, focused interactions to full feature access to prevent overwhelm and direct attention to learning objectives.
2. Principle of Explicit Bridging: Embodied experiences in MR will not automatically transfer to formal mathematics. The design must include intentional, structured activities that make the connections between concrete manipulation, visual representation, and abstract symbolism explicit.
3. Principle of Pedagogical Co-Orchestration: The teacher's role is pivotal in guiding the use of technology. The design must include built-in supports (like structured protocols and dashboards) to empower teachers to facilitate learning effectively rather than merely troubleshooting technology.

This retrospective analysis demonstrates the generative power of DDR. The initial, theoretically grounded design was not discarded but was instead refined and strengthened through its confrontation with reality, resulting in a more robust and effective learning design for MR mathematics education. To consolidate the insights generated from the retrospective analysis, we developed a visual synthesis that organizes the three resulting principles into a practical design reference. This visual "Design Checklist" summarizes how managed cognitive load, explicit representational bridging, and pedagogical co-orchestration operate as mutually reinforcing dimensions of effective mobile MR mathematics learning design. The checklist provides developers, instructional designers, and researchers with a concise tool for evaluating or planning MR-based learning environments (see Table 9).

Table 9. Mobile MR design checklist derived from the retrospective analysis

Cognitive Load	Are features introduced gradually rather than all at once?	• Staged feature release implemented
	Does the interface prevent unnecessary distractions?	• Minimal extraneous controls during each activity
	Are tasks broken into manageable steps?	• Clear task instructions provided
		• Interface does not overload working memory
Representational Bridging	Does the design explicitly connect 3D MR objects to diagrams, symbols, or formulas?	• Visual–symbolic links built into activities
	Are transitions between representations guided, not assumed?	• Prompts guiding students from 3D manipulation to abstraction
	Do students know *why* the MR manipulation matters for mathematics?	• Tasks require explanation, not just exploration
		• Students reflect on representational transitions
Pedagogical Co-Orchestration	Does the design support teachers with clear protocols?	• Teacher instructions and lesson flow provided
	Are there built-in scaffolds that help the teacher guide not just troubleshoot activities?	• Activity stages aligned with teaching goals
	Are teacher dashboards or cues available?	• Tools for monitoring or guiding student work
		• Classroom workflow manageable during MR sessions

5 DISCUSSION

The findings contribute in two ways: (1) they refine design principles for MR-supported mathematics learning based on empirical data, and (2) they show how DDR can produce detailed insight into how immersive technologies interact with classroom pedagogy and student thinking.

5.1 The double-edged sword of engagement: Managing cognitive load in immersive environments

The data show that MR-generated engagement functioned as both an enabler and a constraint. Consistent with prior studies on immersive learning [39], [40], students were highly motivated to explore the MR environment. However, classroom observations indicated that this engagement sometimes produced extraneous cognitive load that interfered with mathematical focus, especially during open-ended exploration.

This pattern was amplified by the initial design choice that allowed unrestricted access to system features. Students frequently interacted with tools unrelated to the current mathematical task, a behaviour consistent with the documented "novelty effect." In response, the retrospective redesign implemented a staged feature release, informed by cognitive load theory [41]. Limiting early feature exposure reduced navigational overhead and redirected students' attention toward core conceptual tasks. This suggests that open-ended MR environments require structured entry phases to ensure that engagement supports rather than competes with learning goals.

5.2 Beyond visualization: The critical need for explicit representational bridging

A recurring difficulty observed in this study was students' struggle to translate MR-supported conceptual understanding into symbolic mathematical expressions. This challenges the assumption that visualization alone is sufficient to support abstraction [30]. The issue was not conceptual misunderstanding of geometry inside the MR environment, but a breakdown when shifting from concrete/visual representations to symbolic forms.

This finding aligns with and extends the work of researchers like Bakker (2018), who emphasize that learning involves movement between different representations [14], and extends it by showing that such movement does not occur automatically in MR contexts. To address this, the redesign added explicit bridging tasks (e.g., From Net to Formula and Formula Derivation activities) that treated representation conversion as an instructional target rather than an expected byproduct.

Student reflections reinforced this diagnosis. One student noted, "*I understood the shapes in MR but sometimes got stuck on paper tests. I needed more practice linking visuals to symbols*" (S09). Another stated, "*When we moved from MR to textbook problems, I missed the interactive visualization. It took time to adjust to static images*" (S26). These statements indicate that the difficulty was representational, not conceptual. Figure 3 illustrates this gap, showing a student who correctly reasoned about volume in MR but produced an incorrect symbolic expression on paper.

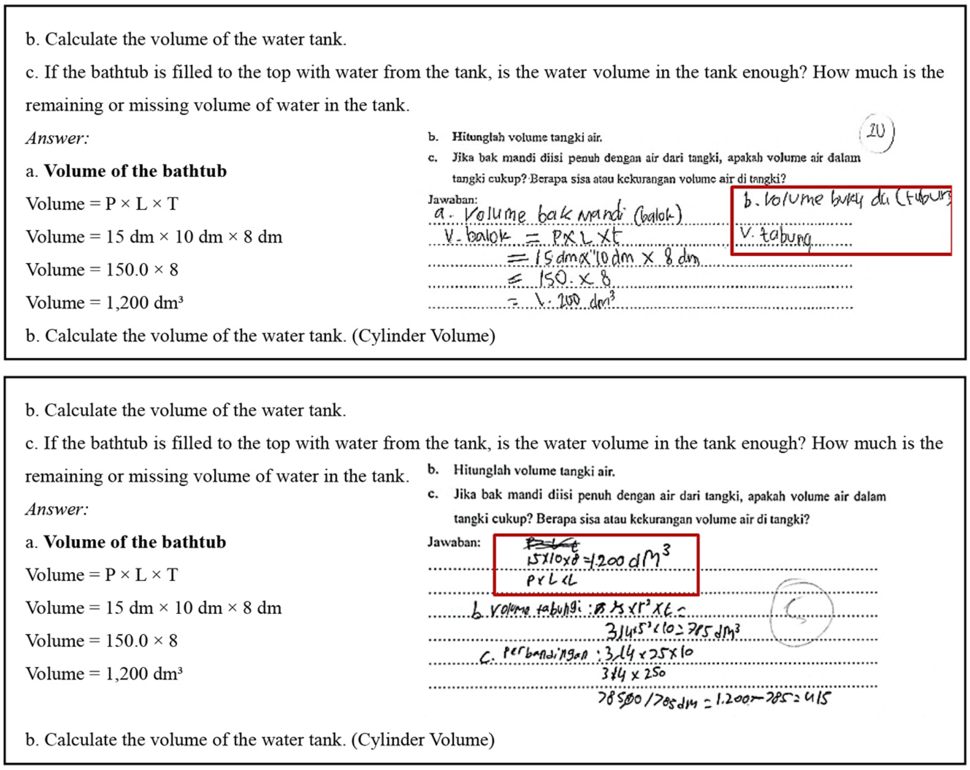

Fig. 3. Example of a student's incorrect symbolic response despite correct understanding in MR

5.3 Redefining the teacher's role: From technical troubleshooter to pedagogical orchestrator

Classroom implementation showed that the introduction of MR changes instructional dynamics and requires teachers to take on new responsibilities. During lessons, teachers spent a substantial amount of time resolving device-level issues (e.g., calibration errors, application restarts, connectivity), which reduced their ability to guide mathematical reasoning and discourse. This pattern aligns with Seufert et al. (2022), who note that immersive technologies introduce additional classroom management demands and technical overhead [42].

The contribution of this work lies not only in identifying this challenge but also in presenting design-based responses that support the teacher's role rather than bypassing it. The retrospective analysis did not recommend minimizing teacher involvement but emphasized the need for tools and procedures that allow teachers to focus on pedagogy. Two mechanisms were introduced for this purpose: an Integrated Teacher Dashboard and Structured Protocols. The dashboard provides real-time visibility into student task progress and basic device status, enabling teachers to intervene pedagogically instead of reactively solving technical issues. The structured protocols standardize device setup, feature activation, and transitions between MR and non-MR tasks, reducing coordination burden during lessons.

This design direction is consistent with human-centered AI approaches to educational technology, which argue that systems should augment, rather than replace, teacher expertise [43]. In this context, the teacher dashboard and structured protocols function as mediating tools that surface relevant information (e.g., task completion, pacing discrepancies, device readiness) needed for classroom orchestration. For MR environments to operate effectively in authentic classroom settings, they must therefore be designed with teacher practices and constraints in mind, allowing teachers to monitor, guide, and coordinate learning activities without being overloaded by technical management.

5.4 Pedagogical co-orchestration under mobile constraints

Classroom implementation indicated that MR demands not only new forms of student activity but also coordinated management of instructional tasks, devices, and pacing. This requirement is referred to here as pedagogical co-orchestration, meaning the alignment of learning activities with device-level and classroom-level conditions in mobile MR environments. Recent bibliometric studies on mobile learning have noted that institutional infrastructure, device variability, and connectivity remain persistent factors shaping mobile-enabled educational environments [44]. In practice, co-orchestration was shaped by cognitive and pedagogical factors, as well as by the constraints of mobile hardware and school infrastructure. Four constraint areas were documented:

1. Screen Size Limitations. Small displays limited shared visibility and made it difficult for teachers to observe student work from a distance. Collaborative groups also had to rotate devices so each student could inspect MR objects, which affected pacing and turn-taking.

2. Battery and Power Availability. Classrooms without reliable charging infrastructure experienced lesson interruptions when devices lost power before planned endpoints. In some cases, devices were rotated among groups to conserve battery, reducing continuity of interaction with MR content.
3. Device Heterogeneity and Performance Variability. Differences in device specifications (e.g., processing power, camera quality, sensor stability) produced uneven performance across students. Some devices rendered MR objects smoothly, while others lagged or required application restarts. As a result, synchronous class-wide activities became difficult to maintain.
4. Device Management in Low-Infrastructure Contexts. Schools with limited device availability rely on shared or borrowed units. This required procedures for allocation, login, calibration, and physical rotation during the lesson, which added to instructional workload rather than remaining a pre-lesson technical task.

These constraints indicate that the success of mobile MR in classrooms depends not only on task design and conceptual scaffolding but also on the orchestration of devices within the operational conditions of the school. Without structured support for co-orchestration, mobile constraints can overshadow the intended learning benefits.

The observed constraints suggest several practical approaches for reducing orchestration frictions in future deployments. For screen size limitations, pairing MR tasks with printed reference sheets or shared displays (e.g., casting to a projector when available) can reduce device handovers and improve monitoring. Battery-related disruptions can be managed through short task cycles (10–15 minutes), rotation schedules planned before class, and battery-status checks integrated into setup routines. To address device heterogeneity, teachers can group students by device performance or use pacing markers (e.g., checkpoints) that allow asynchronous progression without losing instructional coherence. In low-infrastructure settings, simple asset management procedures (e.g., labeled devices, calibration stations, login cards) reduce setup time and lower cognitive load on teachers during lessons.

From a design standpoint, the findings suggest that mobile MR platforms should incorporate features that: (a) provide visibility into device and activity states (e.g., battery, connectivity, task progress), (b) simplify setup and transitions between MR and non-MR tasks, and (c) allow synchronization of activities across heterogeneous devices. Such supports are especially relevant for settings where technical infrastructure is limited and instructional time is tightly constrained. Such supports are especially relevant for settings where technical infrastructure is limited and instructional time is tightly constrained. Related research on the integration of adaptive interactive applications similarly notes that teachers must coordinate pedagogical sequencing with technical and infrastructural considerations [45], indicating that orchestration challenges extend beyond specific technologies such as MR. Taken together, these observations indicate that pedagogical orchestration in mobile MR settings is closely linked to classroom infrastructure and device conditions. This point also provides a basis for the broader implications discussed in the conclusion.

6 CONCLUSION

This study successfully employed DDR to develop and refine a MR platform for elementary mathematics education, specifically targeting the learning of 3D geometry.

The research demonstrates that the iterative DDR process, moving through prospective design, metadidactic implementation, and retrospective analysis, is a powerful methodology for creating pedagogically robust technology-enhanced learning environments. The primary outcome of this process is a set of empirically validated design principles that directly address the critical challenges of implementing immersive technology in authentic classroom settings. The findings reveal that the initial design, while theoretically sound, required significant refinement to achieve its pedagogical goals. The implementation uncovered three central challenges: (1) the dual nature of MR engagement, which can lead to cognitive overload if not carefully managed; (2) the "representational bridge failure," where students struggled to connect concrete MR experiences with abstract mathematical representations; and (3) the unforeseen demands on teachers, who needed to shift from content experts to facilitators of technology-integrated learning. The retrospective redesign introduced staged feature release, bridging activities, and structured teacher supports to address implementation challenges. These changes were informed by observed teacher–student practices, emphasizing that mobile MR integration is shaped not only by task design and scaffolding but also by infrastructural and procedural conditions. Thus, instructional time, device management, and classroom coordination should be treated as integral to technology-enhanced learning design rather than external constraints.

6.1 A framework for mobile MR design

Building on the iterative findings of the DDR cycles, this study proposes the *CORE-MR Framework* (Cognitive Load, Representational Bridging, and Pedagogical Orchestration for Mixed Reality Learning). This framework synthesizes three empirically derived design principles:

1. The Principle of Managed Cognitive Load, emphasizing the need to scaffold immersive experiences through staged feature release and guided interaction.
2. The Principle of Explicit Representational Bridging, which highlights the importance of linking embodied MR experiences to visual and symbolic mathematical representations.
3. The Principle of Pedagogical Co-Orchestration, underscoring the central role of teachers and the necessity of built-in instructional supports.

The CORE-MR Framework offers a transferable model for researchers, instructional designers, and developers seeking to design pedagogically grounded mobile MR applications. It provides a clear, theoretically informed, and practically usable set of guidelines that can be adapted across content areas, grade levels, and educational contexts. This framework is intended to serve as a transferable model for researchers and designers developing mobile MR applications in mathematics and STEM education. The CORE-MR Framework can be seen in Figure 4.

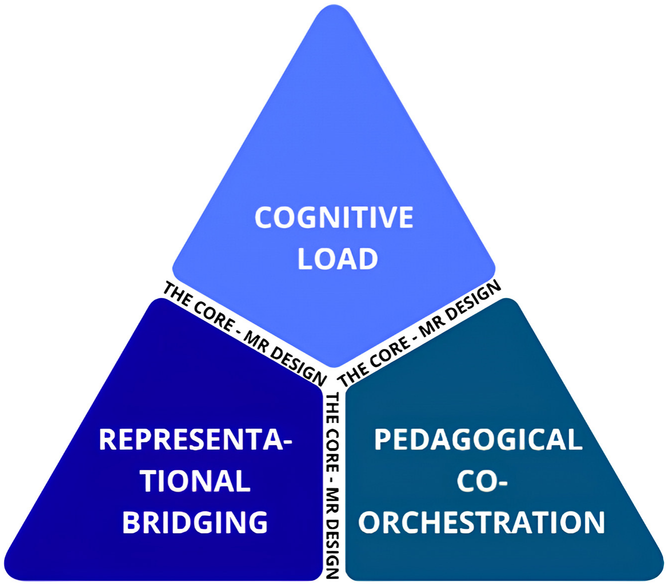

Fig. 4. The CORE-MR framework

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