Reducing Cognitive Load in 3D Geometry with Culturally Responsive Augmented Reality Scaffolds

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ABSTRACT

Mathematical problem solving places heavy demands on students' working memory capacity, particularly when they learn abstract geometric concepts such as three-dimensional curved shapes. Rather than reporting empirical findings, this theoretical synthesis examines the intersection of cognitive load theory, culturally responsive digital scaffolding, and technology-enhanced mathematics learning. Drawing on empirical evidence from cognitive science and mathematics education, we synthesize previous findings and distinguish them from the theoretical propositions developed in this paper. We propose a framework for designing culturally responsive digital scaffolds that reduce extraneous cognitive load while freeing working memory resources for deeper conceptual engagement. The paper synthesizes findings from three interconnected research strands: (1) cognitive load theory and its applications in digital learning environments, (2) culturally responsive mathematics education and ethnomathematics as cognitive scaffolds, and (3) augmented reality (AR) as a tool for reducing cognitive load in spatial reasoning tasks. We argue that culturally familiar contexts reduce the need for effortful translation of abstract symbols, thereby freeing cognitive resources for problem-solving. Furthermore, AR-enabled visualizations externalize abstract mathematical structures, minimize extraneous processing, and facilitate germane cognitive engagement. The proposed Techno-Ethno-Realistic Mathematics Education (TE-RME) framework, which synthesizes digital tools, cultural and ethnomathematical contexts, and realistic problem-solving, integrates these insights to support inclusive, equitable, and meaningful mathematics learning.

ABSTRAK

Pemecahan masalah matematika menuntut kapasitas memori kerja siswa secara intensif, terutama ketika mereka mempelajari konsep geometri abstrak seperti bangun ruang sisi lengkung. Makalah teoretis ini mengkaji keterkaitan antara teori beban kognitif, scaffolding digital yang responsif secara budaya, dan pembelajaran matematika berbantuan teknologi. Dengan mengacu pada bukti empiris dari ilmu kognitif dan penelitian pendidikan matematika, kami mensintesis temuan sebelumnya dan membedakannya dari proposisi teoretis yang dikembangkan dalam makalah ini. Kami mengusulkan kerangka kerja untuk merancang scaffolding digital yang responsif secara budaya guna mengurangi beban kognitif yang tidak relevan sekaligus membebaskan sumber daya memori kerja agar siswa dapat terlibat secara konseptual secara lebih mendalam. Makalah ini mensintesis temuan dari tiga alur penelitian yang saling terkait: (1) teori beban kognitif dan penerapannya dalam lingkungan pembelajaran digital, (2) pendidikan matematika yang responsif terhadap budaya dan etnomatematika sebagai scaffolding kognitif, serta (3) augmented reality (AR) sebagai alat untuk mengurangi beban kognitif dalam tugas penalaran spasial. Kami berpendapat bahwa konteks yang akrab secara budaya mengurangi kebutuhan untuk menerjemahkan simbol-simbol abstrak secara melelahkan, sehingga membebaskan sumber daya kognitif untuk pemecahan masalah. Selain itu, visualisasi berbantuan AR mengeksternalisasi struktur matematika abstrak, meminimalkan pemrosesan yang tidak relevan, dan memfasilitasi keterlibatan kognitif yang bermakna. Kerangka kerja Pendidikan Matematika Tekno-Etno-Realistis (TE-RME) yang diusulkan mengintegrasikan wawasan tersebut untuk mendukung pembelajaran matematika yang inklusif, adil, dan bermakna.

INTRODUCTION

Understanding three-dimensional geometric shapes is a fundamental component of school mathematics curricula worldwide. Mastering concepts such as cylinders, spheres, and cones collectively referred to as curved three-dimensional shapes is essential for developing spatial reasoning, measurement competencies, and problem-solving skills applicable to architecture, engineering, manufacturing, and design (Ruipérez-Valiente & Kim, 2020). However, a substantial body of research has documented the persistent difficulties students encounter when learning these abstract geometric concepts. These difficulties include limited conceptual understanding, challenges in visualizing curved surfaces from two-dimensional representations, and frequent errors when calculating surface area and volume (Kusuma et al., 2023; Sudirman et al., 2023).

To guide this theoretical synthesis, three research questions frame the investigation: (1) What specific cognitive challenges do students face when learning about cylinders, spheres, and cones? (2) How can cognitive load theory explain these challenges and inform the design of instructional scaffolds? (3) In what ways can culturally responsive digital scaffolds, particularly those leveraging augmented reality, reduce cognitive load and support conceptual understanding of curved three-dimensional shapes?

Three primary factors contribute to these learning difficulties. First, the abstract nature of three-dimensional geometry imposes a high cognitive load on learners. Students must engage in mental visualization, transform two-dimensional representations into three-dimensional forms, and perform spatial structuring, all of which demand substantial working memory resources (Sudirman et al., 2023). Epistemological barriers emerge when students attempt to interpret three-dimensional shapes from two-dimensional drawings, identify structural elements such as bases, heights, and curved surfaces, and correctly apply formulas for surface area or volume. Second, many students lack access to innovative, context-rich learning materials. Conventional instruction often relies on static textbook diagrams and formula memorization, which do not convey the spatial structure of curved surfaces concretely (Cherif et al., 2017). The absence of interactive visualization tools hinders students' spatial reasoning and conceptual understanding. Third, the cultural disconnect between students' lived experiences and abstract mathematical content can significantly impede comprehension and performance, especially when instructional materials use unfamiliar cultural contexts.

These challenges align with cognitive load theory (CLT). Initially proposed by Sweller (1988), CLT posits that working memory becomes a bottleneck for learning when information exceeds its limited capacity. As Paas and Van Merriënboer (1994) explained, instructional designers must manage cognitive load by optimizing instruction so that novices can attend to relevant problem characteristics. CLT distinguishes among three types of cognitive load: intrinsic load (inherent in the learning material), extraneous load (imposed by ineffective instructional design), and germane load (devoted to schema construction) (Sweller, van Merriënboer, & Paas, 1998). In three-dimensional geometry learning, the intrinsic complexity of visualizing curved surfaces is often exacerbated by extraneous load from ineffective instructional materials, leaving insufficient working memory capacity for germane processing, namely the deep cognitive engagement needed for conceptual understanding. Research has shown that CLT provides a robust framework for understanding learning in technology-enhanced environments, including those involving dynamic geometry software and three-dimensional representations (Kurban, 2024; Ulusoy, 2022).

To address these challenges, researchers have increasingly explored the integration of technology-enhanced learning tools with culturally responsive pedagogical approaches. This theoretical paper examines three interconnected research strands that converge on a common objective: designing learning environments that reduce cognitive load while supporting meaningful mathematical understanding of cylinders, spheres, and cones. First, we review cognitive load theory and its applications for designing digital scaffolds that externalize abstract mathematical structures. Second, we examine how culturally responsive mathematics education and ethnomathematics can serve as cognitive scaffolds by reducing the effort required to translate abstract symbols into meaningful representations. Third, we analyze empirical evidence on augmented reality (AR) as a tool for reducing cognitive load and enhancing spatial reasoning in geometry learning (Morphew, 2025; Yaniawati et al., 2023). By synthesizing these strands, we propose a framework for culturally responsive digital scaffolds that free working memory resources for deeper problem-solving engagement.

The significance of this theoretical synthesis lies in its potential to guide the design of learning materials that are cognitively efficient, culturally inclusive, and pedagogically effective (Hartoyo et al., 2025). As mathematics classrooms become increasingly diverse, approaches that affirm students' cultural identities while supporting rigorous conceptual development are increasingly important. Furthermore, rapid advances in digital technology offer unprecedented opportunities to externalize abstract mathematical structures in ways that align with the cognitive architecture of human learning.

METHOD

This theoretical synthesis was conducted through a systematic literature review process. Database searches were performed in ERIC, PsycINFO, Scopus, and Web of Science using combinations of the following keywords: cognitive load theory, spatial reasoning, three-dimensional geometry, augmented reality, culturally responsive pedagogy, and mathematics education. The inclusion criteria were: (a) peer-reviewed journal articles and books published between 1988 and 2026, (b) studies addressing cognitive load in mathematics or spatial learning contexts, (c) empirical or theoretical work on technology-enhanced geometry instruction, and (d) research examining cultural factors in mathematics education. The exclusion criteria removed studies focusing exclusively on non-mathematical domains or lacking an explicit connection to cognitive load or spatial visualization. Following the initial screening, articles were compared thematically to identify convergent findings, methodological approaches, and unresolved questions. This comparative analysis informed the synthesis presented below and generated the proposed hypotheses for future empirical investigation.

Although this paper constitutes a theoretical synthesis, it also serves to generate a series of testable hypotheses for future empirical research. To guide subsequent investigations in authentic mathematics classrooms, the following methodological considerations are proposed. The measurement strategies outlined below were selected for their relevance to classroom-based research, balancing practicality with validity. Self-report questionnaires and performance-based measures are particularly well suited to intact classroom settings because they are easy to administer and minimally disruptive to instruction, whereas more resource-intensive methods, such as eye-tracking and physiological measures, may be reserved for controlled laboratory sub-studies.

Cognitive load questionnaires. Self-report measures, such as Leppink et al.'s instrument, distinguish among intrinsic, extraneous, and germane load. These measures are practical for classroom research but rely on learners' metacognitive awareness of their cognitive processing (Karabay & Mese, 2025). For future studies, the level of cultural familiarity, a key moderating variable, can be measured using a pre-intervention Cultural Relevance Survey with Likert-scale items that assess students' prior exposure to and identification with the contextual scenarios presented in the learning materials.

Mental effort ratings. The Paas scale, a single-item measure of invested mental effort, provides a global assessment of cognitive load that correlates with objective performance measures. Ratings can be collected after each problem to track load fluctuations during learning. Secondary task performance. Dual-task paradigms measure cognitive load by assessing performance on a secondary task while learners engage with the primary learning task. Decrements in secondary task performance indicate higher cognitive load on the primary task. This approach provides an objective measure of load, but it requires controlled conditions that may limit its feasibility in regular classroom settings (Gilbert et al., 2023).

Eye-tracking measures. Pupil dilation, fixation duration, and saccade patterns correlate with cognitive load. Eye-tracking provides continuous, objective load measurement without interrupting learning, but it requires specialized equipment and controlled lighting conditions, making it more appropriate for laboratory-based extensions of classroom research. Physiological measures. Heart rate variability, electrodermal activity, and electroencephalography (EEG) can index cognitive load through autonomic nervous system responses. These measures are objective and continuous but require specialized equipment and may be sensitive to individual differences and environmental factors.

Learning outcome measures. Pretest–posttest designs with delayed retention tests assess the effect of cognitive load reduction on learning. Performance on transfer problems that require learners to apply concepts in novel contexts provides evidence of schema construction and germane processing (Nursyahidah et al., 2026). Working memory capacity, which is hypothesized as a moderating variable, can be evaluated using validated span tasks, such as the Automated Operation Span (OSPAN) task or forward and backward digit span tests, which measure individuals' ability to store and process information simultaneously.

Future empirical studies should use multi-method approaches that combine subjective load measures with objective performance measures and, where feasible, physiological or eye-tracking measures to triangulate findings. To ensure ecological validity, these methods should be adapted for integration into naturalistic mathematics classroom settings rather than used exclusively in laboratory environments. The theoretical synthesis presented in this paper suggests the following empirically testable hypotheses for future research on culturally responsive digital scaffolds in mathematics education. These hypotheses are proposed prospectively; they have not been tested in the current study and require dedicated empirical investigation.

H1: Culturally familiar contexts reduce extraneous cognitive load. Students exposed to mathematical problems embedded in culturally familiar contexts, as measured through the pre-intervention Cultural Relevance Survey, will report lower extraneous cognitive load scores and demonstrate higher performance on transfer problems than students receiving culturally neutral or unfamiliar contexts, after controlling for prior knowledge (Hartoyo et al., 2025).

H2: AR-enabled visualization reduces spatial reasoning demands. Augmented reality features including free rotation of three-dimensional objects, dynamic unfolding of curved surfaces (e.g., cylinders and cones into two-dimensional nets), interactive measurement overlays displaying radius, height, and slant height, and direct manipulation of shape parameters are expected to externalize mental transformations and reduce demands on visuospatial working memory. Students using AR tools will demonstrate faster response times and lower error rates on spatial transformation tasks, such as identifying two-dimensional nets and determining dimensions from different viewing angles, than students using static diagrams, as measured by working memory span tasks and reaction-time measures (Morphew, 2025; Yaniawati et al., 2023).

H3: TE-RME-integrated instruction improves germane cognitive load. Technology-Enhanced Realistic Mathematics Education (TE-RME) is hypothesized to increase germane, or relevant, cognitive load rather than merely reducing overall difficulty. The theoretical mechanism is that TE-RME prompts learners to actively map abstract mathematical symbols, such as volume formulas, onto tangible, culturally contextualized objects, such as traditional cylindrical containers or conical structures familiar to students' communities. This mapping process activates prior knowledge, facilitates the construction of richer schemas, and encourages deeper cognitive engagement with the material. Consequently, students learning geometry through TE-RME approaches will report higher germane load scores and lower extraneous load scores than students receiving conventional instruction, as measured by validated cognitive load questionnaires (Karabay & Mese, 2025).

H4: Cognitive offloading mediates the relationship between TE-RME instruction and problem-solving performance. Cognitive offloading strategies—operationally defined as the use of external diagrams to record intermediate steps, step-by-step structured notation prompted by the system, interactive AR manipulation to test spatial hypotheses, and voluntary engagement with digital scaffolding prompts that chunk information—are expected to mediate the effect of TE-RME instruction on mathematical problem-solving performance. Students in TE-RME conditions will spontaneously employ such offloading strategies more frequently than students in conventional conditions (Armitage & Gilbert, 2024; Gilbert et al., 2023).

H5: Individual differences in working memory capacity moderate the effectiveness of TE-RME scaffolds. Students with lower working memory capacity, as measured by OSPAN or digit span tasks, will benefit more from TE-RME scaffolds than students with higher working memory capacity, as predicted by the interaction between instructional condition and working memory span in explaining learning outcomes.

RESULTS AND DISCUSSION

A growing body of research suggests that cultural familiarity can serve as a cognitive resource in mathematics learning. However, this benefit depends on whether the cultural context is mathematically relevant. Mere surface-level familiarity, without meaningful mathematical structure, does not automatically reduce cognitive load. When mathematical problems are embedded in culturally resonant contexts that carry direct mathematical significance, learners may bypass effortful translation between abstract symbols and concrete representations, potentially freeing working memory capacity for deeper relational processing.

Recent empirical findings provide indirect support for this proposition. A comprehensive meta-analysis of ethnomathematics-based learning in Indonesian classrooms, synthesizing 15 quantitative studies involving 1,247 students, reported a large positive effect on mathematical achievement ($d = 1.15$) and a moderate effect on learning attitudes ($d = 0.69$) (Hartoyo et al., 2025). Stronger impacts were observed at the elementary level and in problem-solving tasks. Integrating local crafts, architecture, and traditional games was associated with richer engagement and conceptual understanding. Similarly, a quasi-experimental study in Ghanaian multilingual classrooms involving 160 students found that exposure to culturally familiar mathematical word problems produced significantly higher performance ($M = 7.21$, $SD = 1.64$) than culturally unfamiliar tasks ($M = 5.83$, $SD = 1.59$), with a large effect size ($d = 0.89$). Multivariate regression analysis confirmed that cultural familiarity predicted higher engagement ($\beta = 0.53$, $p < 0.001$), lower anxiety ($\beta = -0.41$, $p = 0.002$), and increased perceived relevance ($\beta = 0.46$, $p < 0.001$).

It is important to note, however, that these studies did not directly measure cognitive load, for example through validated mental effort ratings, dual-task paradigms, or physiological indices such as pupillometry. Rather, they assessed mathematics performance, engagement, anxiety, and perceived relevance. Although improved performance and positive affective shifts are valuable outcomes, they do not automatically constitute evidence of reduced working memory load. Performance gains may arise from increased motivation, lower test anxiety, enhanced persistence, or greater situational interest, all of which are affective pathways that differ from cognitive load effects. Similarly, heightened engagement and perceived relevance, although educationally meaningful, reflect emotional and motivational responses rather than direct indicators of available working memory capacity.

Thus, while these findings robustly demonstrate the value of culturally grounded instruction for affective and achievement outcomes, their interpretation through a cognitive load lens requires caution. The data suggest a plausible mechanism whereby mathematically relevant cultural contexts may reduce extraneous cognitive load; however, this interpretation remains inferential rather than directly empirically validated. Future studies should directly measure cognitive load, ideally using both subjective and objective measures, before attributing these performance gains specifically to freed working memory resources. Distinguishing between affective benefits and cognitive load reduction is essential for developing a precise theoretical account of how culturally responsive scaffolds support mathematical learning.

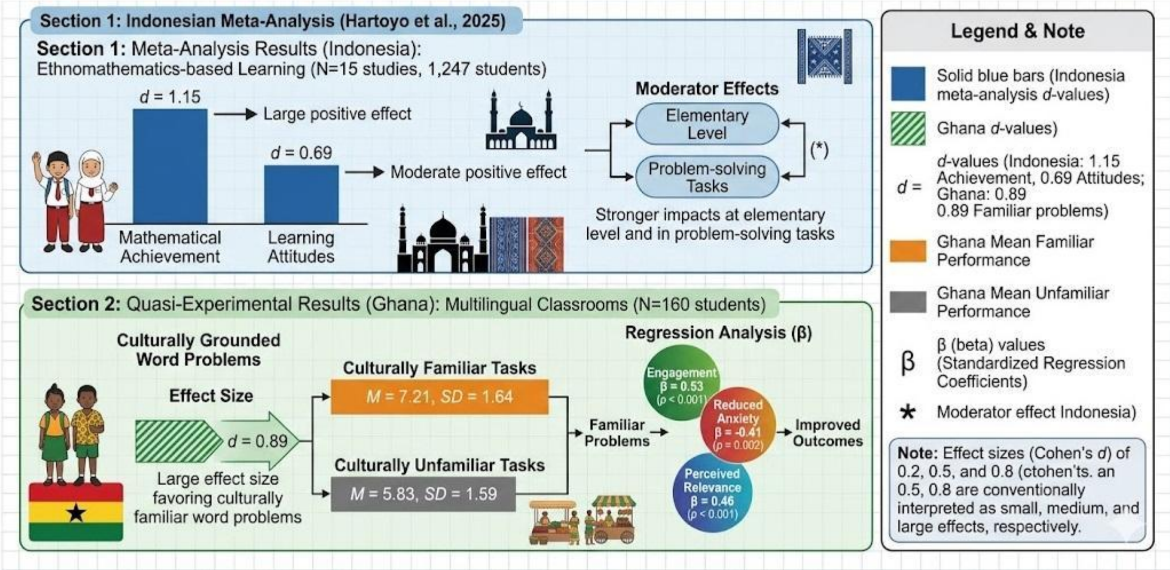

Figure 1. Effect Sizes and Performance Outcomes from Culturally Grounded Mathematics Interventions: Evidence from Indonesian and Ghanaian Classroom Studies

Based on figure 1 presents quantitative findings from two independent culturally grounded mathematics interventions. The left panel displays meta-analytic effect sizes (Cohen's d) from 15 Indonesian studies (N = 1,247) examining ethnomathematics-based instruction. The right panel displays results from a quasi-experiment in Ghanaian multilingual classrooms (N = 160) comparing culturally familiar and unfamiliar mathematical word problems. All effect sizes are expressed as Cohen's d, where values of 0.2, 0.5, and 0.8 are conventionally interpreted as small, medium, and large effects, respectively. The Indonesian meta-analysis yielded two distinct effects: a large effect on mathematics achievement (d = 1.15) and a moderate effect on learning attitudes (d = 0.69). The Ghanaian study produced a large achievement effect favoring culturally familiar problems (d = 0.89); the accompanying bar chart illustrates the raw mean performance difference between the familiar condition (M = 7.21, SD = 1.64) and the unfamiliar condition (M = 5.83, SD = 1.59). The standardized regression coefficients (β) reported beneath the Ghanaian outcomes indicate the unique predictive contribution of cultural familiarity to three affective and motivational outcomes after controlling for other variables: engagement (β = 0.53, p <.001), reduced anxiety (β = −0.41, p =.002), and perceived relevance (β = 0.46, p <.001). Higher positive β values indicate stronger positive associations with culturally familiar contexts, while the negative coefficient for anxiety indicates an inverse relationship: cultural familiarity predicts lower anxiety.

The theoretical framework developed in this paper synthesizes evidence from cognitive load theory (CLT), culturally responsive mathematics education (CRME), and technology-enhanced learning to propose a novel theoretical mechanism: the Technology-Enhanced Realistic Mathematics Education (TE-RME) framework. This synthesis advances the field not merely by combining existing frameworks but by specifying a distinct, testable causal pathway through which culturally responsive digital scaffolds may reduce cognitive load and support mathematical learning.

The paper's unique contribution lies in proposing what we term the dual-pathway hypothesis: culturally responsive digital scaffolds facilitate mathematical learning through two interconnected mechanisms that jointly free working memory capacity. First, culturally grounded contextualization reduces the translation effort required to map abstract mathematical symbols onto meaningful representations, thereby reducing extraneous cognitive load. Second, technology-mediated externalization, specifically through augmented reality (AR), reduces the mental simulation demands associated with spatial reasoning by externalizing visualization and manipulation processes that would otherwise burden working memory. These mechanisms are hypothesized to operate in tandem: cultural familiarity lowers the cognitive cost of accessing mathematical meaning, while AR lowers the cognitive cost of spatial reasoning. Together, they free sufficient working memory resources for germane processing, the deep conceptual engagement necessary for robust schema construction.

This dual-pathway mechanism distinguishes the TE-RME framework from prior integrations of culture and technology. Previous research has documented the engagement benefits of culturally relevant pedagogy (Hartoyo et al., 2025) and the visualization benefits of AR (Morphew, 2025; Yaniawati et al., 2023), but it has not specified how these benefits combine to affect working memory capacity. The TE-RME framework advances a precise cognitive account: culturally relevant contexts reduce element interactivity by chunking familiar referents, while AR reduces intrinsic load associated with spatial transformation. Thus, the framework is not merely a combination of existing approaches but a theoretical integration that generates empirically testable predictions about cognitive processes.

The framework reframes cultural responsiveness as a cognitive resource rather than merely an affective or motivational enhancement. While previous research has documented the engagement benefits of culturally relevant pedagogy, the cognitive load framework explains why culturally familiar contexts may improve learning: they reduce the effort required to translate abstract symbols into meaningful representations, potentially freeing working memory capacity for deeper conceptual processing (Hartoyo et al., 2025). This cognitive explanation has practical implications for instructional design: cultural contexts should be chosen not only for their relevance but also for their potential to reduce element interactivity in the learning task.

Second, the framework specifies mechanisms through which digital technologies—particularly AR—can support learning by externalizing cognitive processes that would otherwise burden working memory. AR reduces the need for mental rotation and mental simulation by providing dynamic, interactive visualizations that students can explore through physical manipulation (Morphew, 2025; Yaniawati et al., 2023). This externalization of spatial processing is particularly valuable in geometry learning, where spatial reasoning demands often compete with mathematical reasoning for limited working memory resources.

Third, the integration of ethnomathematics, Realistic Mathematics Education (RME), and AR into the TE-RME framework provides a comprehensive approach to designing cognitively efficient mathematics instruction (Nursyahidah et al., 2025a; Nursyahidah et al., 2026). Rather than treating cultural context and technology as add-ons to conventional instruction, TE-RME positions them as integral to the learning design process. The framework recognizes that reducing extraneous load is necessary but not sufficient for effective learning; instruction must also promote germane load by engaging students in reflective, meaning-making activities that build robust schemas.

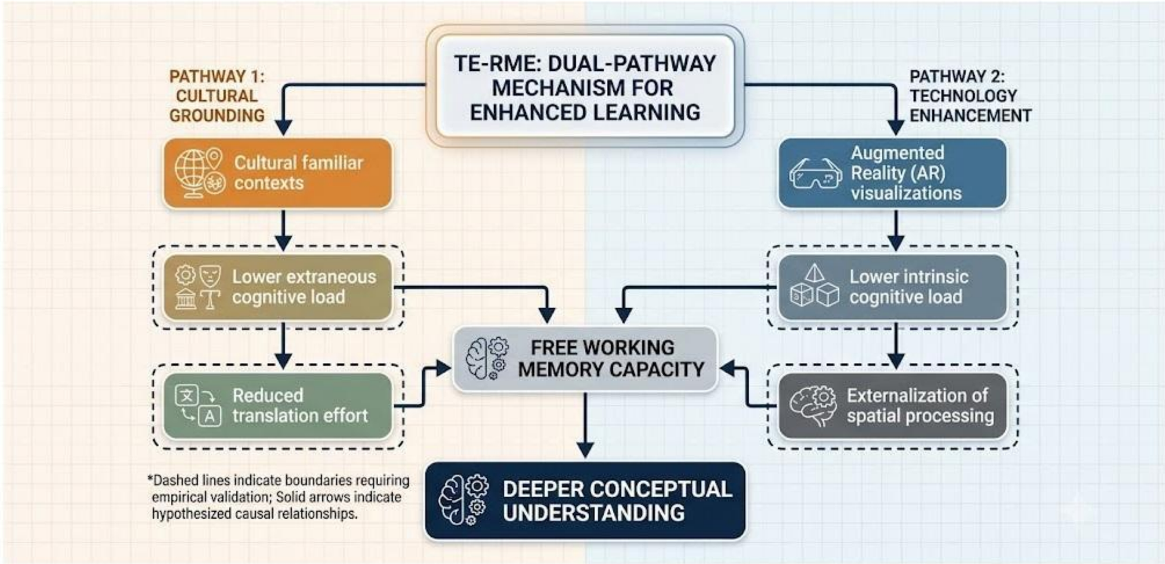

Figure 2. The Technology-Enhanced Realistic Mathematics Education (TE-RME) Framework.

This conceptual diagram illustrates the proposed dual-pathway mechanism of the TE-RME framework. The left pathway (Cultural Grounding) represents the reduction of translation effort through culturally familiar contexts, lowering extraneous cognitive load. The right pathway (Technology Enhancement) represents the externalization of spatial processing through AR, lowering intrinsic cognitive load associated with mental simulation. These pathways jointly free working memory capacity for germane processing, enabling deeper conceptual understanding. Arrows indicate hypothesized causal relationships; dashed lines represent boundaries requiring empirical validation.

As a theoretical synthesis, the proposed TE-RME framework requires empirical validation through rigorous experimental and quasi-experimental studies. The hypothesized cognitive mechanisms—reduced translation effort, externalized spatial processing, and the joint freeing of working memory for germane processing—must be tested using multiple measurement approaches, including validated mental effort ratings, dual-task paradigms, or physiological indices such as pupillometry. Direct measurement of cognitive load is essential because performance gains and positive affective shifts alone do not constitute evidence of reduced working memory load.

Furthermore, the framework's applicability across different mathematical domains, such as algebra, probability, and statistics, and across diverse cultural contexts requires further investigation. Cultural responsiveness is inherently local; therefore, design principles derived from one context may not transfer directly to another without adaptation. Similarly, the effectiveness of AR scaffolds may vary by age group, prior spatial ability, and technological familiarity. These limitations are embedded within the framework itself: the TE-RME framework explicitly acknowledges that the extent of cognitive load reduction depends on the mathematical relevance of the cultural context, the alignment between AR affordances and specific learning objectives, and the progressive formalization from concrete to abstract representations.

Design Principles and Practical Guidance

To support teachers and instructional designers in operationalizing the TE-RME framework, we propose the following design principles:

Principle 1: Select for Mathematical Relevance, Not Mere Familiarity. Cultural contexts should be chosen based on their potential to reduce element interactivity in the specific mathematical content. A context is cognitively beneficial when it embeds the target mathematical structure in a way that students can intuitively recognize. Familiarity alone, without mathematical structure, does not automatically reduce cognitive load and may even introduce extraneous load if students must navigate irrelevant cultural details.

Principle 2: Externalize Spatial Processing with AR. AR should be deployed specifically to externalize cognitive processes that would otherwise impose high intrinsic load, such as mental rotation, visualization of curved surfaces, and transformation between 2D and 3D representations. AR is most valuable when it reduces mental simulation demands that would otherwise burden working memory (Koparan et al., 2023). Designers should identify the specific spatial tasks that are cognitively demanding and match AR affordances to those tasks rather than adding AR as a generic enhancement.

Principle 3: Progressively Formalize from Context to Symbol. Instructional materials should explicitly show the trajectory from contextualized problems to formal mathematical representations (Gravemeijer, 1994; Treffers, 1991). Clear connections between concrete activities, dynamic visualizations, and abstract symbols should be articulated. This progressive formalization supports germane load by guiding students toward schema construction rather than leaving them to infer mathematical structure independently.

Principle 4: Align Scaffolds with Specific Cognitive Demands. Different types of scaffolds address different sources of cognitive load. Cultural contextualization primarily reduces extraneous load, especially translation effort; AR primarily reduces intrinsic load related to spatial simulation; and explicit connections and reflective prompts promote germane load through schema building. Designers should diagnose the primary source of cognitive difficulty for each learning objective and select scaffolds accordingly.

Principle 5: Adapt Locally and Validate Iteratively. Because cultural responsiveness is inherently context-dependent, design principles require local adaptation and iterative validation. What works in one cultural or educational setting may not transfer directly to another. Designers should engage local stakeholders, pilot materials, and refine scaffolds based on observed student difficulties and measured cognitive load outcomes. These principles provide actionable guidance while acknowledging that the TE-RME framework remains a theoretical proposition requiring empirical validation. They are offered as hypotheses to be tested, refined, and adapted across diverse educational contexts.

CONCLUSION

This paper has proposed a theoretical synthesis at the intersection of cognitive load theory, culturally responsive digital scaffolding, and technology-enhanced mathematics education. We advanced a hypothesized mechanism whereby culturally familiar contexts may reduce the effort required for representational translation, potentially freeing working memory resources for deeper conceptual engagement. We further proposed that AR-enabled visualizations may externalize spatial processing demands, thereby reducing intrinsic cognitive load while supporting germane engagement through interactive exploration. The resulting Technology-Enhanced Realistic Mathematics Education (TE-RME) framework integrates these insights into a tentative model for designing learning environments that align with cognitive architecture. These propositions await empirical validation; therefore, the TE-RME framework is presented as a theoretical proposition to guide future inquiry, not as a confirmed or validated intervention.

The theoretical contributions of this paper are threefold, and each addresses a distinct gap in the literature. First, the paper reframes cultural responsiveness in explicitly cognitive terms. Whereas prior work has emphasized affective and motivational benefits, we propose that mathematically relevant cultural contexts reduce extraneous cognitive load by lowering the translation effort required to map abstract symbols onto meaningful, familiar representations. Second, the paper maps augmented reality affordances to specific intrinsic load demands in geometry learning. Rather than citing general visualization benefits, we specify that AR is hypothesized to reduce the cognitive cost of mental rotation and two-dimensional-to-three-dimensional transformation, processes that compete with mathematical reasoning for limited working memory resources. Third, the paper integrates these distinct pathways into a coherent dual-pathway hypothesis, which posits that reducing extraneous load through cultural contextualization and intrinsic load through AR externalization jointly frees sufficient working memory capacity for germane processing. This integration yields a novel, testable prediction about the interaction between cultural grounding and technological scaffolding that neither framework alone can generate.

To evaluate this framework, we propose a sequenced research agenda. Phase 1 should consist of small-scale cognitive validation studies using direct measures of working memory load, such as validated mental effort rating scales, secondary task paradigms, or physiological indicators such as pupillometry, to test the isolated effects of culturally familiar contexts and AR visualizations on cognitive load during geometry tasks. Phase 2 should involve quasi-experimental classroom comparisons contrasting TE-RME scaffolds with alternative conditions, such as culture-only, AR-only, or conventional instruction, to examine their combined effects on learning outcomes and subjective load measures. Phase 3 should progress to larger-scale experimental and longitudinal designs to assess the durability and transferability of effects, as well as moderating variables such as prior spatial ability, cultural familiarity, and grade level. This phased approach would ensure that the framework is rigorously tested before broader claims about its efficacy are advanced.

The potential equity implications of the TE-RME framework are best understood through its proposed cognitive mechanisms. If reducing translation effort and externalizing spatial processing lower working memory demands, the framework may disproportionately benefit students who typically face higher cognitive load due to unfamiliar cultural referents, limited prior knowledge, or less developed spatial reasoning skills. In this sense, the framework offers a plausible pathway for narrowing performance gaps that arise from differential working memory burdens, rather than from differential ability or effort alone. However, this equity hypothesis remains theoretical and requires direct empirical examination. Without such validation, we refrain from claiming that the TE-RME framework inherently guarantees inclusive outcomes. Future research must test whether the hypothesized load-reduction effects are equivalent across student populations and whether they translate into reduced achievement disparities.

In sum, the TE-RME framework offers a theoretical foundation for designing culturally responsive digital scaffolds that work with, rather than against, the cognitive architecture of human learning. Realizing this potential, however, depends on sustained empirical investigation and collaboration among cognitive scientists, mathematics educators, instructional designers, and the communities they seek to serve. The proposed agenda provides a structured pathway for translating this theoretical synthesis into actionable, evidence-based guidance for practice.

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