

The Effectiveness of Immersive AR/VR in Enhancing Mathematical Understanding: A Systematic Review through Bruner's Lens

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Abstract: This systematic review evaluated the effectiveness of augmented reality (AR) and virtual reality (VR) in strengthening understanding of mathematical concepts through the lens of Bruner's enactive, iconic, and symbolic representational stages. Method: A systematic search of Scopus (2021–2026) was conducted following the PRISMA 2020 statement and JBI (2024) evidence synthesis protocol. From an initial pool of 3,641 records, 76 peer-reviewed empirical studies met the eligibility criteria and were retained for synthesis. Methodological quality was appraised using JBI Critical Appraisal Checklist, and findings were synthesized through a narrative-thematic approach. After JBI appraisal, 63% of the included studies were rated as high quality and the remainder as moderate quality (interrater reliability ICC = 0.87). The synthesis showed that AR primarily supported the transition from enactive to iconic representation through collaborative, multimodal interaction. Quasi-experimental findings consistently indicated that immersive technologies outperformed conventional instruction, with effect sizes of $d = 0.44$ to 0.51 and partial $\eta^2 = 0.280$ to 0.378 . Bodily movement and gesture emerged as central mechanisms that supported transitions between representational stages, extending embodied cognition theory to digital learning contexts. The effectiveness of these technologies was further shaped by teacher readiness, instructional design, and cultural integration, particularly the incorporation of local ethnomathematical practices. Taken together, the findings offer an integrative framework for mathematics instruction that connects embodied cognition, AR/VR affordances, and Bruner's developmental sequence, with implications for teacher professional development and culturally responsive instructional design.

Keywords: augmented reality, virtual reality, bruner's representational theory, mathematical concept understanding, immersive learning.

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■ INTRODUCTION

Although understanding mathematical concepts is widely regarded as the foundation for higher-order thinking and problem-solving, many students still struggle to navigate among concrete, visual, and symbolic representations, a skill central to meaningful learning in mathematics. This difficulty is reflected in large-scale assessment data: according to the OECD's PISA 2022 results, only 69% of 15-year-old students across OECD countries reached at least a baseline level

of mathematical proficiency, meaning that on average 31% of students were unable to reliably interpret, translate, and apply mathematical information across representational modes (OECD, 2023). Bibliometric work over the last ten years shows that mathematical representation has become one of the most-researched areas in mathematics education, with increasing attention to visual and symbolic forms and a clear move toward digital technology (Gusteti et al., 2025; Putra et al., 2024). Even with this research

attention, student difficulties remain well documented. Kurt et al. (2023) used Rasch model analysis and found notable variation in middle schoolers' spatial reasoning, particularly on tasks involving mental rotations and spatial orientation. In a related vein, Doz et al. (2022) isolated four factors that influence how students feel about geometry; among them are trouble with visualization and anxiety about abstract representations. Together, these results point to a fundamental teaching challenge: simply showing mathematical representations is not enough; instruction needs to actively support students as they learn to move from one representational mode to another.

Bruner's (1966) theory of representation provides a useful way to think about this problem. He described three stages that build on one another: enactive (learning through action), iconic (learning through images), and symbolic (learning through language and symbols). In his view, deep conceptual understanding develops when learners progress through these stages, whether in a fixed order or through flexible back-and-forth movement. Recent studies back up this staged picture. Cerón-Molina et al. (2025) reported that early problem-solving relies mostly on copying representations, whereas abstract, symbolic work appears only later. Capone (2022) found that the ability to coordinate verbal, iconic, and symbolic systems is a strong predictor of higher-level mathematical understanding, and Hahn and Klein (2025) showed that combining visual and symbolic representations yields a richer grasp of vector field concepts than using a single mode. Taken together, these studies suggest that Bruner's framework remains relevant and that classrooms need to be structured to engage multiple representational modes simultaneously.

It is worth pausing to consider the theoretical fit between Bruner's (1966) framework and the immersive digital environments examined in this review. Bruner's original formulation was grounded in learners'

direct manipulation of physical objects, contexts markedly different from the mediated, screen- and sensor-based interactions that characterize AR and VR. Applying the enactive-iconic-symbolic sequence to digital immersion therefore requires a degree of theoretical extrapolation: virtual manipulation of three-dimensional objects may not engage the same proprioceptive and haptic feedback as handling physical manipulatives, raising the question of whether enactive engagement in a digital space is functionally equivalent to Bruner's original conception. Contemporary scholarship on embodied design (Abrahamson & Lindgren, 2014) suggests that this extrapolation is defensible when immersive technologies preserve the sensorimotor coupling between action and representation, even where the physical substrate differs. This review therefore treats Bruner's framework not as a literal transposition but as an interpretive lens, remaining attentive to instances where the digital medium may transform rather than merely relocate enactive, iconic, and symbolic processes.

Augmented Reality (AR) and Virtual Reality (VR) seem especially well matched to this requirement. In contrast to traditional teaching tools, these technologies allow students to overlay, handle, and engage with mathematical objects at the enactive, iconic, and symbolic levels, all within a single seamless digital space. Hidajat (2024) conducted a systematic review and found that AR tools can enhance cognitive performance, problem-solving, and creativity by providing three-dimensional views and real-time interaction. More recently, Montero-Izquierdo et al. (2025) showed that 3D AR multibase blocks raised positive emotions ($p < 0.001$, medium effect) and self-efficacy ($p < 0.001$, large effect) in primary school children. Turning to VR, Huang et al. (2023) observed a close temporal link between what students said and the actions they carried out together in shared virtual spaces, suggesting that VR can support an embodied way of building geometry knowledge. Stanciulescu et

al. (2024) added to this picture, finding a clear increase in self-efficacy ($t(66) = 3.345$, $p = 0.001$, $d = 0.444$) when students used immersive visualizations in active learning settings. When considered as a whole, these results imply that AR and VR are not just tools that boost motivation; they serve as real cognitive bridges that can activate multiple representational stages simultaneously.

The amount of evidence for this view has grown considerably since 2021. Tursynkulova and Madiyarov (2023) found that learners who worked with AR-based dynamic geometry software scored about 19% higher than controls on planimetry tasks ($p < 0.001$). Chivai et al. (2022) reported that GeoGebra, a dynamic geometry platform, helped students understand solid cross-sections more effectively through interactive 3D displays. Medina Herrera et al. (2024) showed that engineering students who used AR- and VR-based spatial visualization tools improved their mathematical skills substantially compared to a control group ($p = 0.004$, $g = 0.51$). That said, how well these tools work depends heavily on the setting. Munyaruhengeri et al. (2025) found that teachers' views on GeoGebra's usefulness differed markedly according to their years of experience and the training they had received. Wong and Wong (2021) identified distinct motivational profiles among students who used adaptive technology, and Fitria et al. (2025) showed that scaffolding based on single versus multiple representations had different effects on students' conceptual mastery. These inconsistencies make it clear that the success of immersive technology is not simply a matter of the tool itself; how lessons are designed, how prepared teachers are, and how learners differ all matter greatly.

Another contextual element that is just as important but has received less attention is the blending of local cultural knowledge with immersive technology. A handful of recent studies

point to the value of culturally grounded instruction for mathematical learning. Ahmad et al. (2025) found that a realistic mathematics approach rooted in Mandailing culture was effective in fostering critical thinking. Nursyahidah et al. (2025) wove local wisdom into a technology-supported cylinder learning trajectory, making the material more relevant to students. Olivero-Acuña et al. (2025) uncovered ethnomathematical links between the making of coastal cheese and ideas in spatial geometry and proportionality, suggesting that such everyday practices could be incorporated into AR/VR settings. In Indonesia, where the *Merdeka Belajar* curriculum promotes both contextual and digital teaching, this kind of integration looks especially promising.

Even though research on AR and VR in education has grown rapidly, no systematic review has yet to use Bruner's three representational stages as a lens to examine these technologies directly. Reviews that are on topic have taken up other questions. Hidajat (2024) focused on AR and mathematical creativity, while leaving aside the broader representational process and VR. Yusri and Zainal (2025) examined gamification in primary schools without isolating immersive technologies or representation as central ideas. Hasibuan et al. (2025) charted worldwide trends in mathematical proficiency. They argued for a stronger connection between cognitive and affective dimensions, precisely the sort of connection that a Bruner-informed review can make. As things stand, no SLR has adopted Bruner's three-stage theory as its main organizing framework for assessing how AR and VR help learners move enactive to symbolic understanding.

To address this gap, this review is guided by the following research questions, formulated within the PICO (Population, Intervention, Comparison, Outcome) framework, in which Population refers to students in formal mathematics educations at primary, secondary, or tertiary levels; Intervention encompasses AR,

VR mixed reality, and dynamic geometry environments; Comparison involves conventional instruction, such as lecture or textbook-based teaching, without immersive components; and Outcome is defined as measurable improvement in mathematical concept understanding evidenced through representational performance. RQ1. How effective is the use of AR and VR, compared to conventional teaching methods, in enhancing students' understanding of mathematical concepts across Bruner's enactive, iconic, and symbolic representational stages? RQ2. How do AR and VR differentially facilitate students' transitions between these representational stages? RQ3. What contextual factors moderate the effectiveness of AR and VR interventions in mathematical education?

The review draws on peer-reviewed journal articles published between 2021 and 2026, a window chosen to capture the post-2020 surge in immersive technology research in education. PRISMA 2020 and JBI (2024) evidence synthesis guidelines were followed throughout. On the theoretical side, the study aims to extend Bruner's representational theory into the realm of digitally immersive learning and to put forward an integrative framework that connects what AR and VR can offer, the three representational stages, and the idea of embodied cognition. On the practical side, the results are intended to guide instructional design and education policy, especially in systems currently undergoing a digital shift. Figure 1 presents the conceptual framework that guides the remainder of this review.

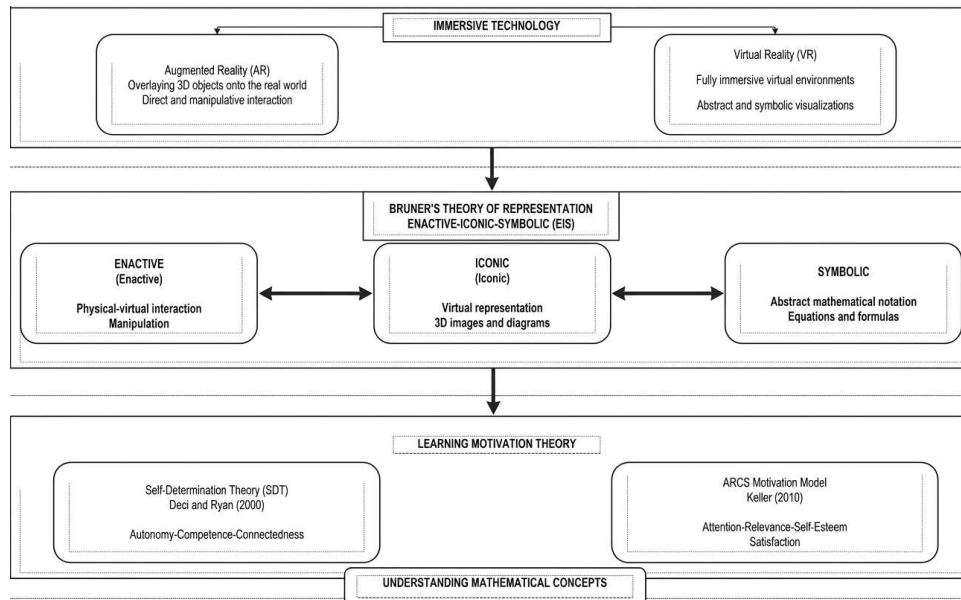


Figure 1. Conceptual framework: integration of immersive technology, bruner's representational theory, and embodied cognition in mathematics education

METHOD

Research Design

The study used a Systematic Literature Review (SLR) design and followed both the PRISMA 2020 statement (Page et al., 2021) and the Joana Briggs Institute manual for evidence synthesis (JBI, 2024). These guidelines were

chosen because they help make the methods transparent and allow other researchers to repeat the work. The review protocol was not registered in advance with a registry such as PROSPERO or the Open Science Framework. Instead, all key decisions, the search strategy, inclusion and exclusion rules, data extraction form, and

synthesis plan were documented before work began and were applied the same way throughout the review to keep the process reliable. Several reasons explain why prospective registration was not carried out, and we acknowledge that this represents a limitation to the transparency of the review process. The specific aspect of the synthesis that required flexibility was the identification of the five reported analytic themes, which were developed inductively through iterative open and axial coding of the extracted findings rather than specified in advance. A fixed, pre-registered protocol would have required us to state these themes and the precise boundaries of Bruner's enactive-iconic-symbolic categories as applied to immersive technology before the coding process had generated them, thereby risking the premature imposition of an analytic structure on the data. PROSPERO mainly deals with systematic reviews of health interventions; although it accepts non-health reviews, registration is not required. Nonetheless, prospective registration remains best practice even for narrative-thematic reviews, as it strengthens transparency and reduces the risk of post hoc selection or synthesis bias; its absence here is therefore acknowledged as a methodological limitation rather than treated as inconsequential. Consistent with established practice in exploratory narrative-thematic reviews (Popay et al., 2007), all procedural decisions were instead documented in full prior to execution and applied consistently throughout, as described above, as a partial substitute for prospective registration.

Search Strategy

The search was carried out exclusively in Scopus. Scopus was selected because it covers a wide range of peer-reviewed work in education, psychology, and educational technology, the main fields relevant to this review. Several practical and methodological reasons

supported the decision to rely on a single database. Scopus indexes more than 85% of the peer-reviewed journals in these areas that are also found in Web of Science (Mongeon & Paul-Hus, 2016; Prancutė, 2021), so its coverage is broad. Working with a single well-curated database also makes research easier to reproduce and avoids problems caused by differing Boolean rules, duplicate records, and indexing delays across databases. Because this review was designed as a narrative-thematic synthesis rather than a meta-analysis that seeks to include every possible study, using a single high-quality database is a defensible approach and has been used before in mathematics education reviews (e.g., Hidajat, 2024). Although the team had only institutional access to Scopus, this constraint was mitigated by Scopus's broad disciplinary coverage and a fully documented search procedure that enables replication or extension. Single-database approaches have been employed in comparable narrative-thematic SLRs in mathematics education (Gough et al., 2017; Hidajat, 2024), and are considered methodologically defensible when the review question is exploratory rather than exhaustive. ERIC was not included as an additional source because its indexing emphasizes education-specific literature and provides limited coverage of the psychology and educational technology journals that this review also draws upon. PsycINFO was likewise not searched, despite its strong coverage of cognitive and educational psychology literature relevant to institutional access constraints. We acknowledge that restricting the search to a single database, even one with broad disciplinary coverage such as Scopus, constitutes a substantive limitation of this review rather than a fully resolved methodological choice, since studies indexed exclusively in Web of Science, ERIC, or PsycINFO may have been missed regardless of the justifications offered above. This limitation will be revisited in future

updates of this review. The research steps are fully described so that the work can be repeated or extended in the future.

The first search was run on 17 October 2025 and updated on 18 March 2026 to capture the latest publications within the review period. The same Boolean string was used both times to ensure the two searches were comparable.

The final research string brought together terms for immersive technology, mathematics education, representational theory, and learners:

("augmented reality" OR "virtual reality" OR "immersive learning" OR "mixed reality") AND ("mathematics education" OR "mathematical learning" OR "conceptual understanding") AND ("Bruner" OR "representation" OR "enactive" OR "iconic" OR "symbolic" OR "CPA model") AND ("student" OR "learner" OR "primary school" OR "secondary school" OR "high school" OR "undergraduate")

Before any manual screening, four automatic filters were turned on within Scopus to put the inclusion criteria into practice right at the search stage: (1) Document type: only "Article" (peer-reviewed journal articles). (2) Publication year: 2021-2026. (3) Subject area: "Social Science," "Psychology," and "Mathematics." (4) Language: No language limits were set in the search string, and the filter was set to include all languages to prevent language bias during retrieval.

No filter for open access status was applied during the database search. Every record that came up, no matter how it was accessed, moved forward for screening. This was done on purpose so that relevant work would not be accidentally left out. Later, when eligibility was being assessed, the full text of each potentially useful article was obtained via open access, institutional subscriptions, or interlibrary loans. After these filters were applied, the updated search (18 March 2026) gave a total of 856 records. The entire search process, from building keywords to applying filters, is shown in Figure 2.

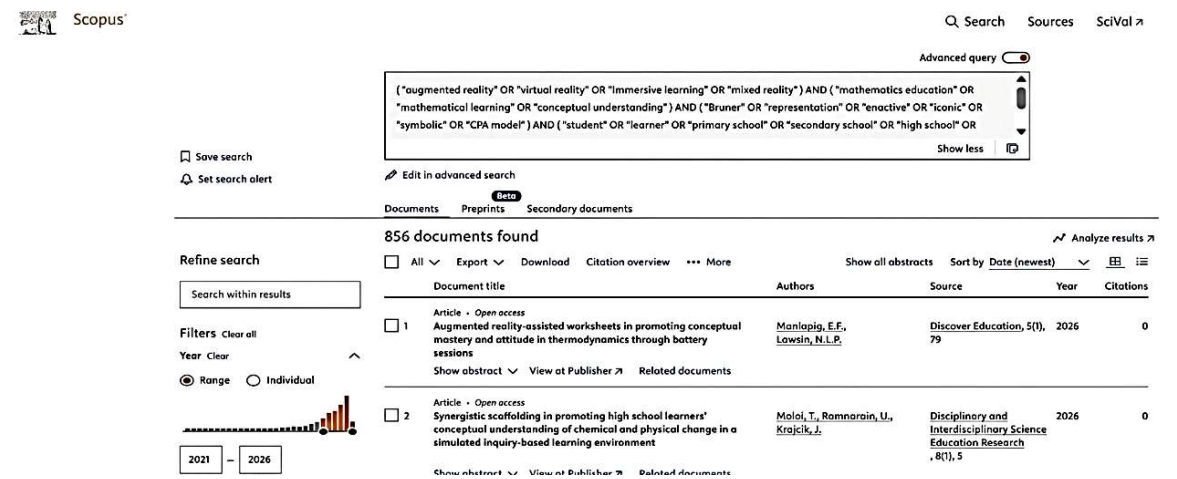


Figure 2. Searching through the scopus database with the same boolean operators

Inclusion and Exclusion Criteria

Eligibility rules were developed using the PICO framework and followed JBI guidelines (JBI, 2024) to ensure studies were selected in a relevant, valid, and consistent manner. Two reviewers worked independently, checking all

records against these rules at each screening step. Nine eligibility dimensions were applied. Records were included if published between 2021 and 2026 and excluded if published earlier. Only peer-reviewed journal articles were included, while proceedings, books, preprints, and editorials

were excluded. Eligible subject areas were limited to education, psychology, mathematics, and educational technology, excluding pure engineering work without an educational context. Eligible technology types comprised AR, VR, mixed reality, and dynamic geometry environments, while 2D simulations and non-interactive video were excluded. The learning focus was restricted to formal mathematics, namely geometry, algebra, number, and calculus, excluding non-mathematics subjects. Eligible research designs included experiments, quasi-experiments, mixed-methods studies, and design-based research, while theoretical reviews without empirical data were excluded. Studies were required to address concept representations or conceptual understanding rather than unrelated representational processes. Full-text accessibility, whether through open access or institutional subscription, was required, excluding records for which only an abstract was available. Finally, studies had to pass the JBI quality assessment with a minimum score of 5 out of 9; studies with lower scores were excluded.

It is worth noting that the Technology Type criterion also admitted seven studies (9.2% of the corpus) that did not themselves employ AR, VR, or a dynamic geometry environment: Sánchez-Ossa et al. (2025), Doz et al. (2022), Küchemann et al. (2021), Balkist and Jupri (2025), El Azzouzi et al. (2025), Yilmaz and Gök (2025) and Al Ali et al. (2024). Each was retained for a specific analytic function rather than as evidence of technology effectiveness. Küchemann et al. (2021) provided a validated instrument, the Representational Competence of Fields Inventory, which is used elsewhere in this review to interpret iconic-to-symbolic transition measures. Doz et al. (2022) and Yilmaz and Gök (2025) characterized learners' and pre-service teachers' baseline attitudes toward and mental

models of representational learning environments, providing the motivating context discussed in the Introduction and the contextual factors theme. Sánchez-Ossa et al. (2025) and Balkist and Jupri (2025) characterized the enactive-iconic-symbolic heuristic and representational competence patterns that immersive tools are designed to support, independent of any specific technology. El Azzouzi et al. (2025) and Al Ali et al. (2024) documented teacher-readiness and representational-training gaps that inform the contextual moderators. None of these seven studies contribute to the synthesized technology-effectiveness comparisons, which are based exclusively on the 69 studies that implemented an AR, VR, mixed-reality, or dynamic-geometry intervention; their role is strictly theoretical and contextual, informing the interpretation of representational constructs and moderating factors rather than serving as evidence for the intervention.

When applying the criteria, we gave preference to empirical work that directly measured the effects of immersive technology on mathematical concept understanding. Studies were excluded if they described a technology without reporting learning outcomes, were purely theoretical with no empirical basis, or addressed non-educational settings lacking a mathematics learning focus. For each full-text article that was removed, a clear reason was written down, and these decisions can be tracked through the PRISMA flow diagram.

A point worth clarifying is how we handled the quality criterion (Criterion 9). We only applied it to articles that had already passed the first eight eligibility rules. This meant that methodological quality was checked in a logical order and in the same way for every study. Articles that passed screening and full-text access were then moved on to full quality appraisal; those that scored

below 5/9 were later excluded. Working in this way kept the assessment of methodological rigor both consistent and open to scrutiny.

The Complete Study Selection Process

Figure 3 lays out the full selection process in a PRISMA 2020 flow diagram. It began with 3,641 records pulled from Scopus. After automatic filters were applied (article only; years 2021-2026; subject areas: Social Sciences, Psychology, Mathematics), 856 records remained for manual screening. Because the research was conducted in a single database, no duplicate records had to be removed. During screening, two reviewers worked separately, reading the titles and abstracts of all records. They marked 156 as possibly relevant and set aside 700 because those papers did not align with the review's topic or aims. Agreement between the two reviewers, measured with Cohen's kappa, was $k = 0,83$ which counts as strong agreement

by the Landis and Koch (1977) standard. When the reviewers disagreed, they talked it through; if they still could not agree, a third reviewer made the final call.

We then tried to get the full texts of the 156 possibly relevant articles. Even after searching open-access sites and using the university's subscriptions, we could not obtain 7 of them. That left 149 articles for a full eligibility check. Two reviewers independently read each full text and measured it against the eligibility rules. In the end, 76 articles met all criteria and were retained for the synthesis. The other 73 were excluded for the following reasons: no empirical data or purely theoretical ($n = 42$), mathematical representation not measured as an outcome ($n = 19$), and technology not immersive or dynamic enough to meet our inclusion bar ($n = 12$). Every reason for exclusion was written down and can be found in the supplementary extraction matrix.

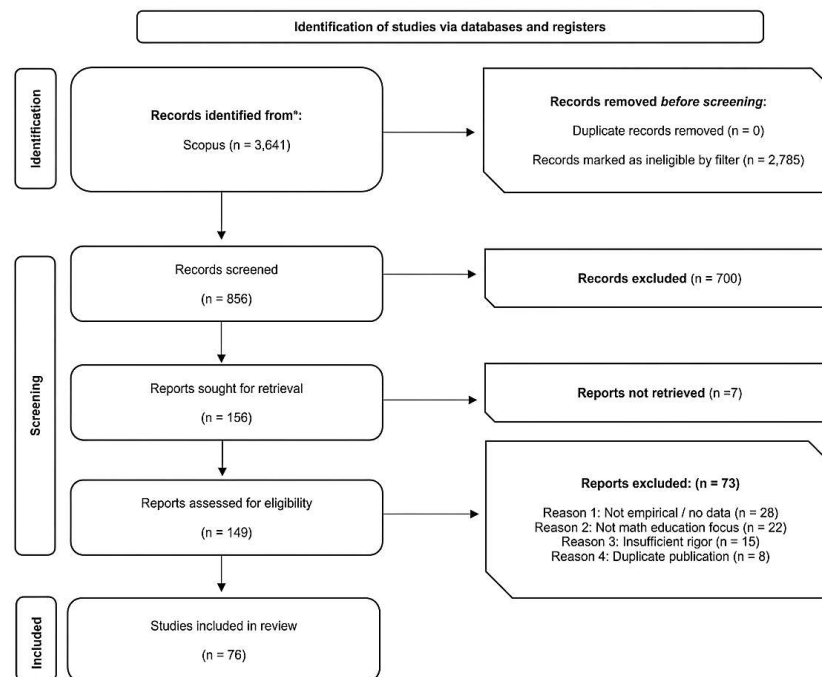


Figure 3. PRISMA 2020 flow diagram: study selection process (source: scopus 18 march 2026)

Data Analysis

Two reviewers independently assessed the methodological quality of each study using the Joanna Briggs Institute (JBI) Critical Appraisal Checklists (JBI, 2024). Because the 76 studies used a range of designs, the right JBI checklist was picked to match the design of each primary study:

1. Quasi-experimental studies → JBI Checklist for Quasi-Experimental Studies (9 items).
2. Qualitative studies → JBI Checklist for Qualitative Research (10 items).
3. Mixed-methods studies → JBI Checklist for Mixed-Methods Research (11 items).
4. Cross-sectional analytical studies → JBI Checklist for Analytical Cross-Sectional Studies (8 items).

For every item, the reviewers gave one of three ratings: “Yes” (score = 1), “No” (score = 0), or “Unclear/Not applicable” (score = 0.5). To compare quality fairly across different designs, each study’s raw score was converted to a 0-9 scale using the formula (raw score ÷ total items) × 9. That way, assessments from different checklists could be placed side by side. The converted scores were then used to put studies into three groups: high quality (7.0-9.0), moderate quality (5.0-6.9), or low quality (< 5.0). Any study that fell into the low-quality group would have been excluded, per Criterion 9.

Regarding research ethics, the JBI Critical Appraisal Checklists used in this review do not include a dedicated item on informed consent or human-subject protection, as these checklists are designed primarily to assess methodological rigor rather than ethical compliance. The presence or absence of explicit ethics statements across the 76 included studies was not systematically tracked during data extraction, which represents a limitation of the quality appraisal process. Studies were not excluded on ethical grounds; journal-level ethical screening during peer review was treated as a baseline safeguard, though this reliance on publisher-level screening rather than

independent verification is acknowledged as a limitation.

Agreement between the two reviewers was assessed using a two-way mixed-effects intraclass correlation coefficient (ICC) for absolute agreement. ICC was used at this stage, rather than Cohen’s kappa, because the quality scores are continuous rather than categorical, and ICC is the recommended statistic for assessing agreement on ordinal or interval-scaled ratings (Koo & Li, 2016). Of the 149 articles that underwent full-text eligibility checking, 73 were set aside, and the reasons were written down in the PRISMA flow diagram. Each of the 76 articles retained for the synthesis underwent quality appraisal. The breakdown was: 63% of the studies ($n = 48$) were rated high quality (7.0-9.0), and 37% ($n = 28$) were rated moderate quality (5.0-6.9). No study landed in the low-quality category. Full JBI score, the checklist used for each study, and the normalized scores can be found in Appendix A.

Data Extraction

Information from 76 included articles was pulled together into a structured matrix. Before using the matrix across all studies, both reviewers tested it on a random set of 5 articles to ensure the coding was consistent and covered everything it needed to. Every article was coded along 13 dimensions: (1) authors and year, (2) title (original language and English translation when needed), (3) journal name, (4) country and participant details (sample size, education level), (5) research methodology and design, (6) instrument and outcome measures, (7) concepts definitions and which of Bruner’s constructs, enactive, iconic, symbolic, were addressed, (8) key findings tied to review question, (9) effect sizes or other statistical information where given, (10) technology type (AR, VR, mixed reality, dynamic geometry environment), (11) how the intervention lasted, (12) relevance rating to the research question (high, medium, low), and (13) reviewer notes and comments.

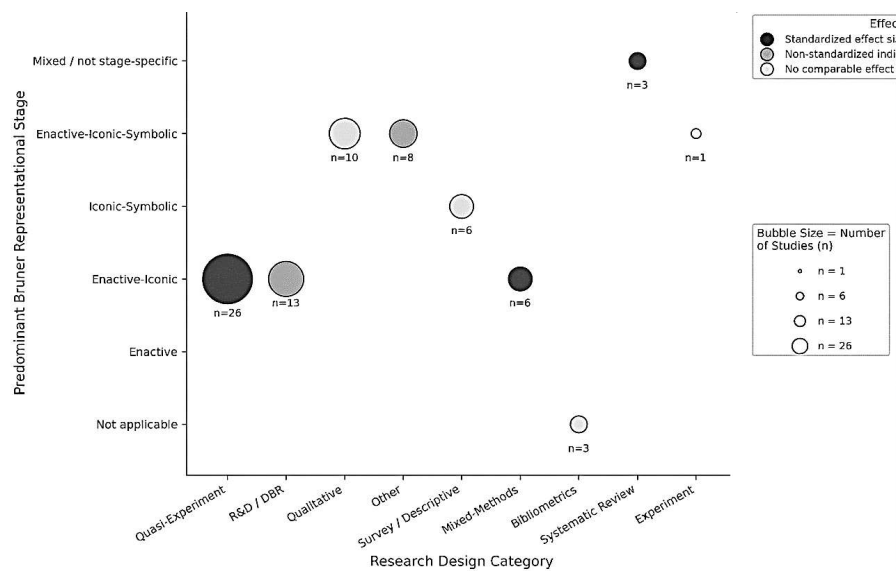


Figure 4. Bubble chart of research design category by predominant bruner representational stage, with bubble size indicating number of studies ($n = 76$ articles). Note: bubble color indicates whether a standardized effect size (Cohen's d , Hedges' g , or partial η^2) was reported for studies in that category; categories relying only on non-standardized indicators (e.g., n -gain, path coefficients) or lacking comparable effect sizes are shown in lighter shades.

Data Synthesis

A narrative-thematic synthesis was carried out, guided by the framework of Popay et al. (2006) and the Synthesis Without Meta-analysis (SWiM) reporting guidelines (Campbell et al., 2020). A meta-analysis was not a good fit here because the 76 studies varied so much, in their design (quasi-experimental, qualitative, mixed-methods, design-based research), the people who took part (from primary school up to university), the kinds of immersive technology used (AR, VR, mixed reality, dynamic geometry), and the ways outcomes were measured (concepts test, spatial reasoning tasks, self-efficacy scales, multimodal interaction logs). On top of that, effect sizes were reported in different forms (Cohen's Hedges' g , partial η^2 , mean differences), and many studies did not consistently report standard errors. Pooling the numbers simply did not make statistical or conceptual sense.

The synthesis moved through three stages, with both reviewers working side by side to keep

the analysis sharp and to cross-check interpretations. The first stage was deductive: a rough thematic frame was built from the review questions and Bruner's three representational stages (enactive, iconic, symbolic), which provided initial ideas for coding. In the second stage, each reviewer independently read and re-read the findings pulled from all 76 articles. They used open coding to spot recurring patterns, possible mechanisms, and contextual conditions that seemed tied to whether AR/VR worked. The two sets of code were then placed side by side: disagreements were discussed until agreement was reached. In the third stage, the codes were sorted into large descriptive themes through axial coding. From there, they were pulled further into five analytic themes that captured the strongest patterns across the whole set of studies.

Table 3 offers a few examples of how the move from open codes to axial categories to analytic themes was made, so that the logic behind the grouping is easier to follow.

Table 3. Example of axial coding from open codes to analytic themes

Open Code (Example from extracted data)	Axial Category	Analytic Theme
"AR enabled 3D manipulation before symbolic notation" (Montero-Izquierdo et al., 2025)	Enactive-to-iconic transition	Theme 1: Role of immersive technologies across Bruner's stages
"VR supported gesture-utterance-action coordination" (Huang et al., 2023)	Iconic-to-symbolic bridging	Theme 1
"Effect size $d=0.44-0.51$ favoring AR/VR over conventional teaching" (multiple studies)	Comparative advantage	Theme 2: Comparative effectiveness
"Action predictions facilitated geometric proof" (Xia et al., 2025)	Embodied mechanism	Theme 3: Embodied cognition
"Teacher training level moderated GeoGebra's usefulness" (Munyaruhengeri et al., 2025)	Teacher readiness	Theme 4: Contextual factors

During axial coding, we repeatedly compared and grouped similar open codes. For example, all codes that had to do with manipulation, gesture, or physical action were placed under "enactive mechanism." These axial categories were then drawn upward into the five analytic themes. The full coding tree can be requested from the authors.

The five analytic themes that came out of this process are: (1) the role of immersive technologies across Bruner's representational stages; (2) comparative effectiveness relative to conventional methods; (3) the function of embodied cognition in immersive learning; (4) contextual factors that moderate implementation

success; and (5) theoretical and practical implications of the synthesized evidence. Each theme is reported in the Results and Discussion section as narrative, supported by representative primary studies and, where possible, quantitative effect sizes. The breakdown of articles by research design is shown in Figure 5.

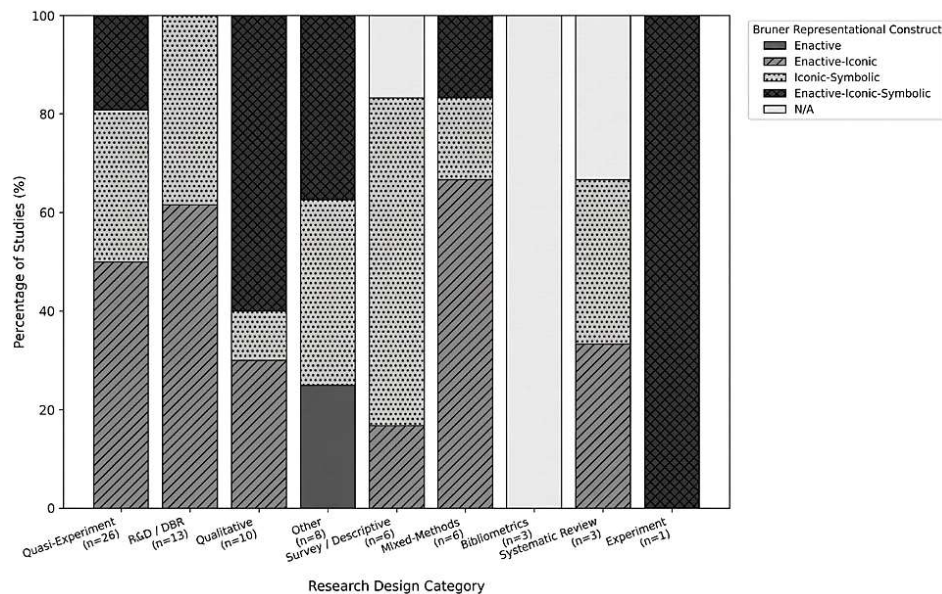


Figure 5. Distribution of Bruner's representational constructs across research design categories (N = 76 articles)

■ RESULT AND DISCUSSION

Below, we present a narrative-thematic synthesis of 76 articles, organized around the five analytic themes outlined. We first examine how different immersive technologies map onto Bruner's representational stages (Theme 1), and then compare their effectiveness with conventional instruction (Theme 2). The section that follows takes up the role of embodied cognition as an underlying mechanism (Theme 3) and the contextual conditions that shape whether these tools succeed (Theme 4). Finally, we discuss the implications of the findings for theory and practice (Theme 5). Throughout, individual studies are cited not as one-off data points but as illustrations of broader patterns that kept appearing across the full set of papers.

Augmented Reality and the Enactive-Iconic Transition

One thing that came up again and again in the AR-based studies was that being able to handle three-dimensional virtual objects-layered right onto the physical space-let learners carry out mathematical operations before they turned those actions into visual, iconic representations. Montero-Izquierdo et al. (2025) gave a clear example: primary school children who worked with 3D AR multibase blocks not only moved virtual cubes around but also showed real gains in positive emotions ($p < 0.001$, medium effect) and self-efficacy ($p < 0.001$, large effect). This suggests that the enactive, hands-on part of the task built both thinking skills and emotional readiness for the iconic stages. Tursynkulova and Madiyarov (2023) found that students who built geometric shapes with AR-based dynamic geometry software did 19% better than the control group on planimetry tasks ($p < 0.001$). The key seemed to be interactive 3D views: students could turn and look at shapes in real time, and the physical movement fed directly into visual understanding. Similar results were

reported in the work of Chivai et al. (2022), who found that GeoGebra, a dynamic geometry platform, helped students grasp solid cross-sections through interactive visuals, and in the work of Nadzri et al. (2024), whose AR modules led to clear gains in both conceptual and procedural knowledge among primary learners. Scippo et al. (2025) added weight to the value of digital manipulation, showing that digital tessellation tasks in primary schools led to clear improvements over control groups ($t(30)$ significant). On the other hand, Deswita et al. (2025) examined a mobile app without AR or VR features and found only a modest gain ($N\text{-gain} = 0.4$), with just 40% of learners reaching mastery. The contrast helps to bring out what immersive, hands-on interaction adds beyond ordinary digital media.

Virtual Reality and the Iconic-Symbolic Transition

Where AR was particularly good at linking action to visual representation, VR stood out for connecting visual (iconic) and abstract (symbolic) modes. Huang et al. (2023), using multimodal interaction analysis in a shared VR space, observed a tight temporal link among what students said (symbolic), the gestures they made (enactive), and what they did on screen (iconic). This suggests that VR allows learners to work with multiple representational modes simultaneously, which aligns well with the iconic-to-symbolic shift. Stanciulescu et al. (2024) backed this up with numbers, reporting a clear rise in self-efficacy ($d = 0.444$) when students used large-scale immersive visualization displays in active learning settings, demonstrating that even non-headset visualization technologies can support the iconic-to-symbolic transition when deployed within well-structured active learning environments. Within the corpus, Küchemann et al. (2021) contributed a methodological foundation to this transition by validating the

Representational Competence of Fields Inventory among 515 first- and third-semester STEM students using Rasch scaling, confirming that the capacity to move between visual field-line representations and symbolic vector notation constitutes a coherent and measurable competence. Although this study did not itself deploy an AR or VR intervention, it was retained in the corpus because the validated instrument

directly underpins the interpretation of representational competence outcomes reported elsewhere in this review. Beyond the current corpus, complementary evidence from Edelsbrunner et al. (2023), who applied the same inventory, further supports this position, showing that the ability to move between visual and symbolic forms is a central component of conceptual understanding among undergraduates.

Table 4. Systematic comparison of AR and VR in the context of Bruner's representational stages

Dimension	Augmented Reality (AR)	Virtual Reality (VR)
Bruner Stage	Enactive-Iconic (Tursynkulova and Madiyarov, 2023; Montero-Izquierdo, 2025; Nadzri, 2024)	Iconic-Symbolic (Huang, 2023; Stanciulescu, 2024; Medina Herrera, 2024)
Mechanism	3D overlay; direct manipulative interaction; real-time feedback; physical-virtual spatial exploration	Fully immersive environment; collaborative multimodal representation; free 3D navigation; abstract simulation
Effectiveness Evidence	19% geometry improvement; large effect on self-efficacy; all van Hiele levels significant	Self-efficacy $d=0.444$; (large-scale display); strong multimodal coordination; visualization $p=.004$; $g=0.51$
Optimal Context	Geometry, measurement, number, ethnomathematics, digital manipulatives	Algebra, vectors, function visualization, collaboration, higher-order problem-solving
Embodied Cognition	Virtual object manipulation (Lee-Cultura, 2022; Xia, 2025; Rahmasari & Kuswanto, 2023)	Gesture-utterance-action coordination (Huang, 2023; Abdu, 2025; Shvarts and Van Helden, 2023)
Limitations	Device quality dependent; potential visual distraction in classrooms	High device cost; motion sickness potential; social isolation; learning curve; some included studies used large-scale display systems rather than head-mounted VR, which limits strict comparability

Note: AR = Augmented Reality; VR = Virtual Reality. Bruner's stages of classification are based on the predominant representational transition observed across studies, not an exclusive assignment

Toward an Integrated Representational Mechanism

Taken together, the findings paint a picture of AR and VR serving as cognitive bridges. These tools tighten the links between bodily action, visual perception, and symbolic abstraction. Immersive interaction seems to engage motor and visual pathways simultaneously, and this joint activation appears to help build more lasting and organized conceptual representations. The ideas align with principles of embodied cognition, which hold that mathematical learning is rooted in physical

experience and spatial awareness, not solely in the manipulation of abstract symbols. More support comes from Melhem et al. (2025), who used a multisensory Concrete-Representational-Abstract (CRA) approach and found gains across all van Hiele levels of geometric thinking ($p < 0.001$), with visual methods leading the shifts between representations. Temaj et al. (2025) added converging evidence: combining visual and experiential approaches led to a clear grasp of the function concepts (posttest $M = 64.87$ vs pretest = 53.43). Even where pretest differences

were not significant, as in Kholid et al.'s (2022) study of GeoGebra-based project work, the advantage appeared once tasks required dynamic visualization, which backs the claim that immersive tools push the iconic-to-symbolic shift when representational flexibility is needed.

In a real sense, these results take Bruner's theory a step further and resonate with, while also extending, broader theoretical currents beyond this corpus of primary studies. The finding that representational stages can be activated simultaneously rather than sequentially aligns with dynamic systems accounts of cognitive development (Thelen & Smith, 1994), which similarly reject strict linear staging in favor of concurrent, context-sensitive processes. It also converges with Nathan's (2021) account of grounded and embodied mathematical cognition, which argues that gesture and perception continue to scaffold symbolic reasoning well beyond the point where symbolic competence is first achieved, rather than being abandoned once abstraction is reached. At the same time, this simultaneity complicates Bruner's (1966) original developmental ordering, suggesting that immersive digital environments may not simply accelerate movement through his stage but instead reorganize their relationship altogether. In immersive digital settings, representational understanding can deepen through multisensory work, and transitions between stages need not follow a fixed order. Instead, these shifts can occur simultaneously because the technology allows learners to engage with mathematical objects at multiple representational levels within a single seamless learning experience. This idea lies at the heart of the integrative framework shown in Figure 1.

Effectiveness Compared to Conventional Methods

Across the quasi-experimental studies, one of the strongest and most stable findings was the

clear edge that immersive and dynamic technologies had over conventional instruction. This pattern held up across different measures of effect sizes, educational levels, and cultural settings. Still, a note of caution is needed: the numbers come from individual studies, not from a pooled meta-analysis. Because the studies varied so much in design, setting, and outcome measures, a quantitative synthesis was not possible, a point we return to in the limitations section. To make sense of the variety, we organized the synthesis around two questions: how large were the reported effects, and how consistent were the findings across different contexts. Although almost all studies reported an advantage for immersive technologies, the magnitude of that advantage varied widely, which calls for a closer look at the conditions associated with larger and smaller effects.

Magnitude and nature of the advantage

A good number of the reviewed studies turned up large effect sizes. A digital learning platform in Morocco, for instance, showed a large effect on both achievement and long-term retention (ANCOVA, partial $\zeta^2 = 0.280$, $p < 0.001$; En-nhiri et al. (2025), a digital game built to strengthen spatial representational produced large effects on object observation (partial $\zeta^2 = 0.378$) along with a medium effect on mental rotation (partial $\zeta^2 = 0.082$; Liu et al. (2025). Large effects of this kind usually appeared when the technology enabled learners to engage in sustained, interactive manipulation over several sessions. This pattern aligns with the idea that more immersive engagement leads to stronger learning outcomes.

Medium-to-large effects were common as well. Work that used GeoGebra in social-cultural settings (Ndagijimana et al., 2024) or that brought AR into dynamic geometry tasks (Tursynkulova & Madiyarov, 2023) found clear between-group differences. This strengthens the view that the

representational bridging described earlier feeds directly into measurable gains. Even when studies reported only raw score differences rather than standardized effect sizes, the gaps between experimental and control groups were often large. An Android-based mathematics tool, for example, pushed posttest scores to 84.09 compared with a control mean of 51.10 (Kusuma et al., 2025).

Not every study, however, found large effects. When immersive technology was used as an additional resource rather than the primary teaching vehicle, gains remained statistically significant but were more modest. In a STEAM setting, an interactive learning environment led to a clear improvement in understanding of geometry with a moderate effect ($t(98) = 8.200, p < .001$; Dildabayeva & Zhaydakbayeva, 2024). Game-based embodied learning also showed clear pre-to-post gains, but the difference between groups was not always dramatic when the control group also received active instruction (Georgiou & Ioannou, 2021). These finer-grained findings suggest that the extent to which immersive technologies help depends on how the instruction is designed, what the comparison group is doing, and how sensitive the outcome measures are, not simply on the technology itself.

Robustness across contexts and culture

Just as striking is how consistent the advantage was across different settings, clear gains showed up in Algebra in achievement through connectivity technology in the United States (Pape et al., 2022), in conceptual mastery of molecular geometry with virtual simulations in Indonesia (Stiawan et al., 2022), in trigonometric competency with GeoGebra in Colombia, where the state of students rated as weak in reasoning fell sharply (Carriazo-Regino et al., 2024), and in mathematical representation skills among pre-service teachers and pharmacy students in Indonesia using epistemic problem-solving approaches (Sridana et al., 2025).

The Indonesian studies are especially relevant for the cultural lens of this view. AR mobile media (mean score 67.5; Yaniawati et al., 2023) and an ethnomathematics-based Realistic Mathematics Education e-module (Palinussa et al., 2025) both produced highly significant posttest differences, even when the technology was used in a fairly modest way. Alongside evidence from Morocco, Taiwan, and Rwanda, these findings suggest that the benefits of immersive technologies are not limited to particular cultural or economic conditions, as long as the instruction is designed with local circumstances and learners in mind.

Overall, the comparative advantage of immersive technologies over conventional methods holds up well, with medium-to-large effects documented across a variety of mathematical topics and cultural settings. At the same time, the spread in effect sizes highlights how much implementation quality, intervention intensity, and outcome-measure sensitivity really matter. Because no formal meta-analysis could be conducted, the patterns described here should be treated as consistent signals rather than exact estimates.

The Role of Embodied Cognition in Immersive Learning

One of the most important findings from the synthesis is that embodied cognition is not just a side effect of immersive technology; it is a core mechanism that propels learners from one representational stage to the next. AR and VR can bring several representational levels into play at once. The studies discussed here go further, showing that bodily experience makes that activation possible. Three strands of evidence, all connected, help explain the role of embodiment: (a) action and gesture as routes to abstraction, (b) the link between neuromotor coordination and enactive representation, and (c) physical interaction with objects as something that builds representations.

Action and gestures as bridges to abstraction

Several studies found that when learners act out mathematical ideas through gestures or whole-body movement, they create a path from physical action to abstract symbols. Xia et al. (2025) ran a randomized controlled experiment and found that predicting an action helped geometric reasoning. The group that made predictions showed not only a non-significant trend toward slightly greater insight ($p = .071$) but also produced noticeably stronger mathematical proofs. Although the between-group difference in insight scores did not reach statistical significance, the quality of mathematical reasoning in the prediction group was notably higher, suggesting that preparing to move may prime symbolic reasoning even when immediate gains in insight are modest. Lee-Cultura et al. (2022) identified three distinct problem-solving styles in children using motion-based technology: informed, trial-and-error, and random. Children who showed the informed style, marked by purposeful movement, understood geometry more accurately, which tells us that it is the quality of hands-on engagement, not just whether it happens, that makes a difference for learning. Shvarts and van Helden (2023) gave a strong example of how sensory-motor experience can link physical action and mathematical abstraction in distance learning. Students who traced sine curves with their bodies ended up better at building and reading sine graphs, a bodily rhythm turned into a symbolic function.

Neuromotor coordination as a marker of enactive representation

If enactive engagement truly supports representation, we should see its traces in how perception and motor systems work together. Abdu et al. (2025) provided direct evidence, showing that the back-and-forth balance between eye and hand is a reliable sign of ongoing mathematical learning. Their work places enactive

representation inside Bruner's framework as something we can observe at the neuromotor level; eye-hand coordination becomes a bodily marker of concept formation. Tancredi et al. (2021) strengthened this view by showing that using both hands together to handle virtual objects was clearly linked to elementary students' grasp of proportionality. These studies move the conversation away from abstract metaphor and toward measurable behavior, giving real substance to the idea that enactive representation has a neurological and behavioral basis.

Physical interaction with objects as a driver of representational construction

Beyond purely digital settings, studies that used real objects or AR overlays confirmed that direct physical contact speeds up representational shifts. Jablonski (2023) compared mathematical modeling with real objects, photos, and texts, and found that working directly with real objects led to clearly different modeling times and solution quality. The hands-on experience yielded measurable cognitive advantages, supporting the first stage of Bruner's sequence. Rahmasari & Kuswanto (2023) applied the same idea to AR: a problem-based learning pocketbook that combined AR with local wisdom did a much better job than PowerPoint or standard textbooks at raising mathematical and graphical representation skills ($p < .001$). Kämpf et al. (2025) also observed that students who actively worked with trochoid models in physics showed greater cognitive engagement than those who only observed, confirming that embodied interaction, whether with physical or AR-enhanced objects, strengthens representational construction.

When these three lines of evidence are pulled together, a clear mechanism appears: bodily action, gesture, coordinated movement, or direct handling of objects provides the experiential ground on which iconic and symbolic representations are later built. This fits neatly with

the “cognitive bridges” idea, introduced in immersive technology, which helps learners move through Bruner’s stages by drawing the body into the process as a representational tool. The enactive stage is not something to leave behind; it stays coupled with iconic and symbolic processing, especially when AR and VR keep multiple modes of engagement alive.

Contextual Factors of Success

Immersive technologies do not have a fixed level of effectiveness. Instead, a set of contextual factors shapes how strongly they influence understanding of mathematical concepts, sometimes boosting their effects and sometimes watering them down. Working through the 76 articles, three broad groups of contextual influences stood out: (a) teacher readiness and instructional design, (b) weaving in local cultural knowledge, and (c) individual differences among learners. Importantly, these factors do not act in isolation; they interact, and their interplay can strengthen or weaken the representational gains.

Teacher readiness and instructional design

Time and again, the teachers’ preparedness emerged as one of the strongest moderating factors. Munyaruhengeri et al. (2025) surveyed 218 mathematics teachers in Rwanda and found that views on GeoGebra’s usefulness varied widely with teaching experience and training. This underlines that adopting a tool is as much about pedagogical readiness as about the tool itself. Similar findings were reported in studies that examined how digital scaffolds are built. Fitria et al. (2025) showed that using single-representation versus multiple-representation scaffolding online led to different levels of concept mastery, which means the complexity of representational support has to be tuned carefully. Wong and Wong (2021) also found clear motivational profiles among students working with adaptive technology (overall $M = 3.56$, $SD = 0.49$), a sign that a one-size-fits-all design will not work.

The way the technology is designed matters too. Yahya et al. (2024) reported that an AR-based geometry module was effective, and that three of five predictors were significant in logistic regression; the difference lay in the module’s structural features, not simply in its use of AR. Karim et al. (2024) applied social cognitive theory to an AR learning kit for physics and mathematics, and a needs analysis revealed that all participants wanted a contextualized form of AR. Firmansyah et al. (2025) added to the picture by finding that a contextual electronic module raised both self-efficacy and problem-solving, reinforcing the point that technology needs to be embedded in meaningful, well-thought-out instruction. All of this points to one conclusion: immersive technology is only as effective as the pedagogical thinking that surrounds it, the preparation of teachers, the grain size of representational scaffolding, and the extent to which instruction is shaped to fit the context.

Integration of local cultural knowledge

A different but equally strong contextual layer concerns how well the technology aligns with local cultural practices and knowledge, often referred to as ethnomathematics. A clear pattern emerged: when immersive or mobile technologies were tied to cultural points learners already knew, their effectiveness increased. Ahmad et al. (2025) showed that a realistic mathematics model grounded in Mandailing culture and supported by TPACK fostered contextually grounded critical thinking. Nursyahidah et al. (2025) showed that blending local wisdom with technology to design a cylinder learning trajectory, using the Realistic Mathematics Education approach, led to meaningful conceptual understanding.

These results reach beyond Indonesia. Olivero-Acuña et al. (2025) uncovered ethnomathematical links between coastal cheesemaking in Colombia and concepts in spatial geometry, measurement, and proportionality, pointing to untapped

opportunities for immersive technology. In Indonesia, Panjaitan et al. (2025) reported that learning media based on Batak culture sparked high interest, with 85% of students saying they enjoyed the work. The pattern is unmistakable: when instruction speaks to students' cultural identities and everyday practices, immersive technology becomes more than new gadgets; it becomes a culturally sustaining representational bridge. This connects with earlier findings that visual and iconic representations grow stronger when they feel personally meaningful.

Individual learner differences

In addition to teacher and cultural factors, learner characteristics also shape how well the technology works. Balkist and Jupri (2025) noted that slower learners encountered their main difficulties with operational thinking and applying numbers, while higher-achieving students moved easily between representations. This difference calls for differentiated immersive scaffolding. Yılmaz and Gök (2025) examined pre-service teachers' drawings and found that concrete and contextual representations were consistently identified as the most important features of ideal learning environments, suggesting that learners themselves value easy access to representations. Al Ali et al. (2024) reported that the extent to which pre-service teachers solved word problems varied greatly with their representational ability, and they argued for representational training to begin during teacher education. Finally, Jiang et al. (2025), using structural equation modeling, found that informal mathematics activities involving technology had a clear impact on mathematical interest (direct effect = 0.343, $p < 0.001$), which in turn fed into academic achievement. This shows that informal, technology-rich settings can shape the motivational-cognitive environment in which AR/VR interventions take place.

Putting it all together, the success of immersive technologies depends on three things

working in concert: teachers who are well prepared and use well-designed instruction, content that is both personally and culturally relevant, and a sensitivity to the wide spread of learners' representational skills and motivations. These contextual conditions help explain the variation in effect sizes and inform the development of practical advice.

Theoretical and Practical Significance

The findings of this review have important implications for theory, practice and future research. On the theoretical side, they extend Bruner's (1966) representational framework into the sphere of digitally immersive learning in a way that meaningfully advances the original model. On the practical side, they provide concrete steps for instructional design, teacher professional development, and the use of culturally responsive technology. Both are addressed below.

Theoretical implications: taking Bruner's theory into immersive contexts

The most important theoretical move is that the evidence challenges the usual linear reading of Bruner's stages. It shows that immersive technologies can activate the enactive, iconic, and symbolic modes in parallel rather than sequentially. As discussed earlier, AR enables learners to interact with 3D virtual objects (enactive) and observe their visual changes (iconic). At the same time, VR allows gestures to be converted to symbolic notation in real time. The simultaneous activation turns Bruner's ordered stages into a dynamic, multimodal back-and-forth.

This change is driven by embodied cognition. Bodily action—gesture, object handling, eye-hand coordination—is not a temporary scaffold that disappears when symbolic understanding is reached. It continues to be an active resource of representation, still grounding and steadying abstract thought. A new integrative framework is emerging (see Figure 1) as this insight is associated with the “cognitive bridges”

metaphor: Immersive technologies '!' Embodied interaction '!' Simultaneous activation of representations '!' Deeper conceptual understanding. In this framing, AR and VR function as representational amplifiers: they extend the body's ability to enact, visualize, and symbolize mathematical ideas within a single, seamless digital space.

This rethinking also adds a cultural dimension to Bruner's theory, which was largely absent from the original version. The power of immersive representational bridges increases when they are grounded in local cultural practices and knowledge systems (ethnomathematics). The framework thus takes for granted that learning representation is cognitive and embodied but also culturally situated.

Practical implications: translating findings into actionable strategies

The practical aspect refers to the three contextual pillars: teacher readiness, instructional design, and cultural integration. Regarding teacher preparation, the evidence that teachers' views of technology change markedly with training and experience (Munyaruhengeri et al., 2025) means that professional development has to move well past basic software skills towards what could be called representational pedagogy, the ability to design and run learning experiences that deliberately lead students through the enactive, iconic, and symbolic stages with immersive tools. Digital representational facilitation should be a core competence of teacher education programs, especially in the context of *Merdeka Belajar* in Indonesia.

Regarding instructional design, the finding that single- and multiple-representation scaffolding produce different learning results (Fitria et al., 2025) suggests a graduated scaffolding model. Here, support is built in incrementally to match the learners' increasing skills. Learners would begin with immersive

enactive scaffolds (AR manipulatives) that are gradually faded out as iconic and symbolic scaffolds (VR visualizations, dynamic notation) are introduced. Designers should avoid overwhelming learners with all representational modes at once without guidance, as this can overload working memory, which aligns with cognitive load theory discussed under future research.

Regarding cultural integration, the strong findings on ethnomathematics (Ahmad et al., 2025; Nursyahidah et al., 2025; Panjaitan et al., 2025) suggest the need for immersive learning modules that use local cultural references as a launchpad for representational work. For instance, AR geometry modules could start with culturally familiar objects, e.g., the traditional structure of Batak houses for 3D geometry, before switching to generic symbolic notation. The iconic stage is therefore not only visual but also meaningful, which tightens the bridge to symbolic understanding.

Directions for future research

There are several useful directions for future work. Longitudinal designs are the most pressing need; they can tell us whether the simultaneous representational activation seen in short-term studies persists and generalizes over time. The integrative framework developed above also needs to be tested directly (e.g., studies comparing linear vs. simultaneous representational sequences in AR/VR settings). The intersection of embodied cognition, cognitive load theory, and motivational design remains relatively unexplored, and future work could investigate how to tune immersive scaffolds to address intrinsic cognitive load while leveraging embodied engagement. Cross-cultural comparative studies are needed to determine whether the advantages of culturally anchored immersive technologies are generalizable across ethnomathematical traditions. Finally, the prevalence of quasi-experimental designs signals a need for more rigorous,

preregistered randomized controlled trials that can bolster causal claims.

One promising approach in the Indonesian context is the systematic development and testing of immersive modules grounded in ethnomathematics and aligned with the *Merdeka Belajar* curriculum. Such work would contribute to the theoretical understanding of culturally situated representational learning while also providing practical tools for classrooms.

Strengths and Limitations

Several methodological and conceptual strengths support confidence in the conclusions drawn here. Firstly, the whole review followed PRISMA 2020 guidelines and was guided by the JBI manual for evidence synthesis (JBI, 2024). As a result, all steps from searching to synthesis are transparent. Secondly, two independent reviewers performed the selection and quality appraisal, and the inter-rater reliability was calculated at screening (Cohen's $\kappa = 0.83$) and quality assessment (ICC = 0.87). The use of two reviewers and a third reviewer to resolve disagreements reduces the likelihood of selection bias and increases the reliability of the final set of studies. Third, while the decision to restrict to peer-reviewed journal articles is a limitation (see below), it did impose a minimum level of methodological quality across the included work. The JBI appraisals also support this, with 63% of the studies rated high quality and none rated below moderate. Fourth, each article was coded on 13 dimensions using a pilot-tested extraction matrix, and all coding decisions were traceable in the supplementary extraction file. The full extraction matrix, including studies used primarily for contextual triangulation rather than direct citation in the narrative synthesis, is available as a Supplementary File. Conceptually, combining Bruner's representation theory and embodied cognition provides a novel theoretical perspective that goes beyond describing whether AR/VR

works and instead offers an integrative explanatory framework.

At the same time, several caveats need to be kept in mind when interpreting the results. First, the search was conducted only in Scopus; Scopus is interdisciplinary and covers education, psychology, and educational technology well, but some relevant journals may not be indexed there. We may have missed studies indexed in Web of Science, ERIC, or regional databases such as SINTA or SciELO. Future updates should include multiple databases and, where possible, grey literature to build a fuller picture. Secondly, the review is affected by publication bias, as only peer-reviewed journal articles were considered. Research with null or negative results is less likely to be published, which may create a false impression of the effectiveness of immersive technologies. The absence of dissertations, preprints and technical reports suggests that the evidence presented here is likely biased toward positive outcomes.

Third, the range of research designs (from quasi-experiments to qualitative case studies) meant that a quantitative meta-analysis was not possible. The narrative-thematic synthesis was conducted using established guidelines (Popay et al., 2006; Campbell et al., 2020), but is interpretive in nature. Effect sizes from individual studies (e.g., Cohen's d , partial η^2) are reported as signals, not as pooled estimates of one common underlying effect. In this sense, it is necessary to be careful when assessing the size of the advantage of AR/VR over conventional means. Fourth, despite careful quality assessment, a practical trade-off was made. Scores from the different JBI checklists (ranging from 8 to 13 items) were normalized to a 0–9 scale. This allowed for comparisons, but the conversion has not been psychometrically tested, and the labels “high” and “moderate” should be understood as relative rather than absolute. Fifth, the majority of the studies were done in urban, well-resourced

schools, mostly in Asia, Europe, and North America. Whether the findings hold in rural or under-resourced settings remains an open question. Sixth, the review's publication window (2021–2026) covers a period of accelerated research in immersive educational technology, but it also excludes earlier foundational work that might have offered further insights. Seventh, no language limits were applied to the search string, but the Boolean search string was in English and may have resulted in the retrieval of mostly English-language publications. Thus, some non-English-language work may have been missed. An additional limitation concerns the inclusion of a single psychometric instrument validation study (Küchemann et al., 2021) that did not itself employ an AR or VR intervention, but was retained because its validated measure of representational competence directly informs the interpretation of iconic-to-symbolic transitions reported elsewhere in this review. Eighth, this review did not independently verify whether each

included primary study reported explicit ethics approval or informed consent procedures. Ethical compliance was assumed to have been screened at the publication stage by the respective journals rather than independently re-verified during data extraction, which is a limitation future reviews with greater resources may wish to address.

These limitations do not invalidate the main conclusions of the review, but they do put bounds on the interpretation of the findings. Future review search strategies should include multiple databases, multiple languages, and grey literature. Where there is sufficient methodological similarity, formal meta-analyses should be conducted to obtain overall effect sizes and to explore moderators such as education level, technology type, and intervention duration. Longitudinal studies are also needed to establish whether the representational gains documented here persist over time and transfer to tasks that do not involve immersive tools. Figure 6 shows the distribution of articles by year of publication.

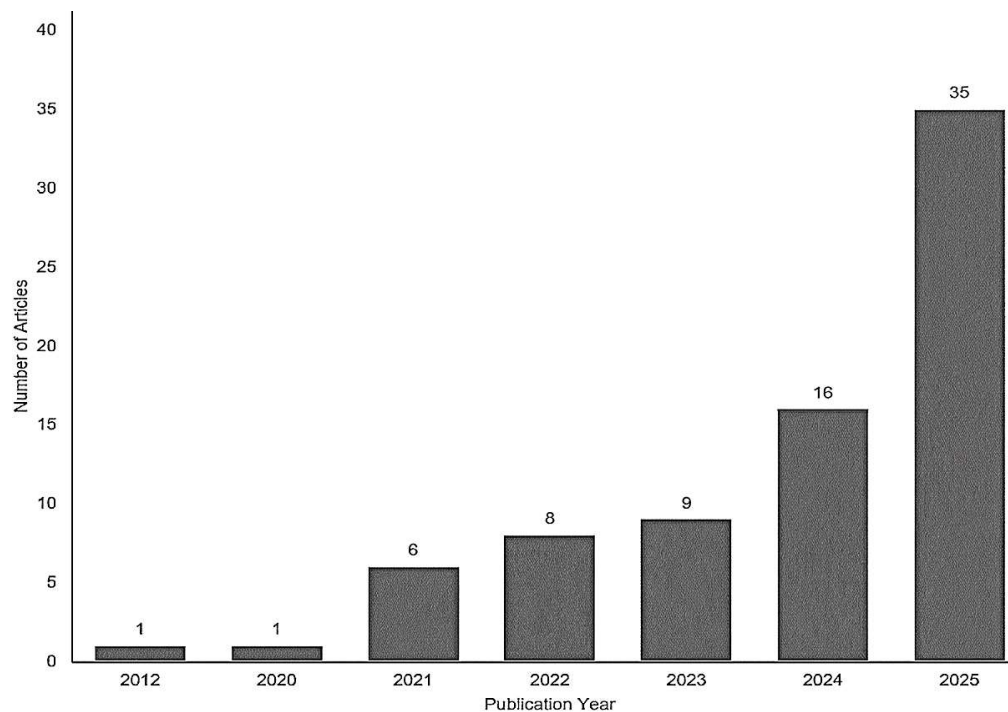


Figure 6. Distribution of 76 included articles by publication year (source: scopus, 18 march 2026)

■ CONCLUSION

The question addressed in this review was whether AR and VR can assist learners in building mathematical understanding via Bruner's enactive, iconic, and symbolic stages. The evidence from 76 empirical studies published between 2021 and 2026 is clear: when embedded in well-planned instruction, these technologies can make a real difference in how students learn through representations. Three general conclusions stand out, each with its own theoretical and practical import.

First, there was a clear relationship between some technologies and some stages. The enactive and iconic stages were reliably supported by AR and dynamic geometry tools, which enable students to manipulate three-dimensional objects and observe their changes on screen. In contrast, VR was more closely associated with the shift from iconic to symbolic work, in which collaborative and multimodal representation helped bridge gesture, speech, and abstract notation. This gives educators a principled way to choose technology: AR to ground abstract ideas in tactile, embodied activity, and VR to connect visual experience with formal symbols.

Secondly, not all the effects are a matter of hardware or software. Bodily action—gesture, object manipulation, coordinated movement—emerged as a key mechanism linking enactive experience and symbolic understanding. This finding extends Bruner's theory one step further. In digital spaces, students do not have to pass through the stages in order; motor, visual, and symbolic work can all occur simultaneously within a single integrated experience. The framework presented in this review (Figure 1) incorporates that idea by conceptualizing immersive technologies as cognitive bridges between embodied action and the emergence of representation.

Third, the effectiveness of AR and VR is not a fixed property of the technology itself but is

substantially moderated by contextual factors, including teacher readiness, instructional design quality, and individual learner characteristics. This finding directly answers the review's guiding question by clarifying that immersive technology alone is insufficient; its impact on understanding of mathematical concepts depends on the pedagogical and contextual scaffolding with which it is deployed.

Returning to our guiding question, the data are unequivocal in showing that AR and VR are more effective than traditional instruction at building mathematical understanding. The advantage is greatest when the technology is purposefully matched to the targeted stage, AR for grounding concepts in action (enactive-to-iconic) and VR for linking visual work with symbols (iconic-to-symbolic), and when the work is supported by solid teacher preparation and instruction that fits the context. At the same time, the magnitude of that advantage varies from study to study. A meta-analysis was not possible, and the numbers should be read as suggestive signals rather than final estimates.

The practical message is clear. Teachers must be seen as reflective facilitators of digital representational learning, and instructional design must be attuned not only to what a particular technology can do but equally to the cultural backgrounds and cognitive profiles of the learners. These findings point to the importance of investing in teacher professional development and in developing open, flexible, immersive resources that can be localized for use by policymakers and curriculum designers. Future work will need to move beyond short-term quasi-experimental designs and ask if the representational skills built through immersive technologies persist and generalize to mathematical tasks that do not use those tools. The effect estimates reported here can be refined through searches across multiple databases, the inclusion of grey literature, and formal meta-

analyses. Cross-cultural studies that intentionally vary the degree of cultural integration built into AR and VR designs would also illuminate the conditions under which these tools work best. A promising direction for integrating ethnomathematics into immersive technology in Indonesia and elsewhere is to deepen conceptual understanding while affirming the cultural identities that learners bring into the mathematics classroom.

■ DECLARATION OF GENERATIVE AI USAGE IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) employed QuillBot (quillbot.com) to assist with paraphrasing and language refinement of selected passages. Claude (Anthropic, claude.ai) was used to support grammatical proofreading and language editing. The author(s) have thoroughly reviewed, edited, and verified all content processed through these tools and assume full responsibility for the accuracy, integrity, and originality of the published article. All citations, data, and scientific claims were verified independently against their sources by the authors.

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