EDUMATSAINS
JURNAL PENDIDIKAN MATEMATIKA DAN SAINS
E-ISSN:2527-7235
Volume 10 Issue. 4, April 2026, pp 54-68
http://ejournal.uki.ac.id/index.php/edumatsains

Exploring the Potential Alignment between VR/AR and Universal Design for Learning for Mathematics Accessibility in Elementary Schools: A Systematic Literature Review

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Article Info

Article history:
Received: December 9th, 2025
Revised: April 19th, 2026
Accepted: April 22nd, 2026
Available online: April 30th, 2026

https://doi.org/10.33541/edumatsains.v10i4.7632

Abstract

Mathematics instruction in elementary schools often presents accessibility challenges, particularly for learners who struggle with abstract and symbolic concepts. Universal Design for Learning (UDL) provides a flexible framework to support diverse learners through multiple means of representation, engagement, and expression. In addition, immersive technologies such as Virtual Reality (VR) and Augmented Reality (AR) offer opportunities to visualize mathematical concepts and create interactive learning experiences. This study aims to explore the potential alignment between VR/AR and UDL in improving accessibility in elementary mathematics learning. A systematic literature review of studies published between 2015 and 2024 was conducted, involving eight empirical studies analyzed through thematic synthesis. The findings show that VR/AR can support conceptual understanding, increase student engagement, and provide multiple ways for students to express their understanding. This study contributes to understanding how immersive technologies can support UDL principles in mathematics learning. The findings also suggest that teachers can use VR/AR to design more inclusive learning experiences, supported by adequate training and infrastructure. However, challenges such as limited devices, teacher readiness, and technical constraints need to be considered in implementation.

Keywords: Virtual Reality, Augmented Reality, Universal Design for Learning, Accessibility, Elementary Mathematics

1. Introduction

Mathematics is a foundational subject in elementary education, yet it often presents significant challenges for young learners. Many students experience difficulties in understanding abstract and symbolic mathematical concepts, particularly when learning is dominated by textbooks and teacher-centered instructional approaches. According to Piaget (1952), children at the elementary level are generally in the concrete operational stage, which means they rely heavily on concrete experiences to understand new concepts. As a result, abstract ideas in mathematics, such as geometric relationships, number patterns, and symbolic representations, can be difficult for them to grasp. These challenges are even more pronounced among students with diverse learning needs, especially those who benefit from visual supports, hands-on activities, and multimodal learning experiences. Consequently, mathematics often becomes a subject where learning barriers emerge early and continue to affect students' engagement, confidence, and long-term academic achievement.

To address these challenges, Universal Design for Learning (UDL) has been widely recognized as an effective framework for supporting inclusive and accessible education. Rose and Meyer (2002) define UDL as an approach that emphasizes the need to design instruction that anticipates learner variability rather than adapting instruction after barriers arise. The framework is based on three core principles: providing multiple means of representation, engagement, and action and expression. Through these principles, UDL encourages teachers to use diverse instructional strategies, flexible learning materials, and varied assessment approaches to accommodate differences among learners. Empirical studies support the effectiveness of UDL in improving accessibility and participation in inclusive classrooms. Rao, Ok, and Bryant (2021) found that UDL-based practices can enhance student engagement and reduce learning barriers across different educational settings. Wulandari and Suryana (2022) also reported that the implementation of UDL contributes to more equitable learning opportunities in elementary schools, particularly in classrooms with diverse student characteristics.

In parallel with the development of inclusive pedagogical frameworks, advances in educational technology have introduced new possibilities for supporting mathematics learning. Among these, immersive technologies such as Virtual Reality (VR) and Augmented Reality (AR) have gained increasing attention. VR enables learners to engage with fully simulated environments, allowing them to explore mathematical concepts through interactive and embodied experiences. Meanwhile, AR integrates digital elements into real-world contexts, making it possible for students to visualize abstract mathematical ideas in more concrete and meaningful ways. Ibáñez and Delgado-Kloos (2018) demonstrate that augmented reality can enhance learning outcomes in STEM education by providing interactive and visual learning experiences. Chen and Liu (2022) show through a meta-analysis that VR and AR environments can improve both cognitive and affective outcomes, including conceptual understanding, motivation, and engagement. These findings suggest that immersive technologies hold considerable potential for supporting mathematics learning, particularly in making abstract concepts more accessible to learners.

Despite these promising findings, most existing studies on VR and AR tend to focus primarily on learning outcomes, such as academic achievement and student engagement. There is still limited attention given to how these technologies can support accessibility and address learner variability in a systematic way. This indicates a significant gap in the literature, especially in relation to how immersive technologies can be aligned with inclusive pedagogical frameworks such as UDL. This study does not only examine the effectiveness of VR and AR in improving learning outcomes, but also focuses on how these technologies can be interpreted through the UDL framework to support accessibility in elementary mathematics learning. By shifting the focus from performance outcomes to accessibility and inclusion, this study offers a different perspective on the role of educational technology in mathematics education.

Furthermore, although VR and AR offer promising opportunities, their alignment with UDL principles should not be assumed without careful consideration. Several studies have identified potential challenges associated with the use of immersive technologies in education. Akçayır and Akçayır (2017) report that AR can introduce technical difficulties and usability issues that may disrupt the learning process. In addition, Parong and Mayer (2018) found that immersive virtual environments may increase cognitive load, which can negatively affect learning if not properly managed. Radianti et al. (2020) also highlight broader challenges, including limited access to devices, high implementation costs, and the need for adequate teacher training. In the Indonesian context, these challenges are further compounded by disparities in technological infrastructure and variations in teacher readiness. These issues may contradict UDL principles that emphasize equitable access and the reduction of learning barriers. Therefore, it is important to critically examine not only the potential benefits but also the limitations of VR and AR in supporting inclusive mathematics learning.

Based on these considerations, this study aims to examine the potential alignment between VR/AR and UDL in the context of elementary mathematics learning. Specifically, this study seeks to: (1) analyze how VR and AR can be interpreted through the principles of UDL; (2) evaluate their potential in enhancing accessibility for diverse learners; and (3) identify challenges and contextual factors influencing their implementation in educational settings. By synthesizing findings from previous empirical studies, this research is expected to contribute to both theoretical understanding and practical implementation of accessible and inclusive mathematics learning supported by immersive technologies.

2. Methods

Research Design

This study employed a Systematic Literature Review (SLR) to examine how Virtual Reality (VR) and Augmented Reality (AR) can support accessibility in elementary mathematics learning from the perspective of Universal Design for Learning (UDL). The SLR approach was selected because it enables a structured, transparent, and reproducible synthesis of empirical evidence (Kitchenham & Charters, 2007). Rather than focusing on the number of included studies, this review emphasizes the depth of thematic analysis to identify meaningful patterns across studies related to UDL principles. The review process followed the PRISMA 2020 guidelines (Page et al., 2021) to ensure methodological rigor and transparency.

Search Procedure

The literature search was conducted using several reputable academic databases, including Scopus, ERIC, ScienceDirect, SpringerLink, and Taylor & Francis. These databases were selected due to their coverage of peer-reviewed and high-quality research in education and technology. Google Scholar and the Indonesian SINTA index were used as supplementary search sources to ensure comprehensive coverage of relevant studies. These sources were not treated as primary databases, and all identified studies were cross-checked to confirm their peer-reviewed status and eligibility based on the inclusion criteria.

The search was conducted using the following Boolean search string:

“Universal Design for Learning” OR “UDL” AND

“Virtual Reality” OR “VR” OR “Augmented Reality” OR “AR” AND

“mathematics”AND

"elementary school" OR "primary school".

The publication period was limited to 2015–2024 to capture recent developments in immersive technology and inclusive pedagogy. All retrieved records were exported into a reference manager to facilitate duplicate removal and screening.

Inclusion and Exclusion Criteria

To ensure focus and relevance, the following inclusion criteria were applied:

1. Published between 2015 and 2024
2. Empirical research articles (qualitative, quantitative, mixed-methods, experimental, or R&D)
3. Examined VR and/or AR in educational contexts
4. Focused specifically on mathematics learning at the elementary or primary school level
5. Published in peer-reviewed journals and available in full text.

Studies were excluded if they:

1. Focused on secondary or higher education
2. Did not involve mathematics content
3. Were review articles (systematic reviews or meta-analyses) to avoid double counting of evidence
4. Lacked sufficient methodological clarity
5. Were duplicates.

Screening and Selection Process

The screening process followed the PRISMA framework, consisting of identification, screening, eligibility, and inclusion stages. A total of 183 articles were initially identified from all databases. After removing duplicates, 152 articles remained. Title and abstract screening resulted in 80 articles selected for full-text review. After applying the inclusion and exclusion criteria, 8 studies were included in the final synthesis.

The final number of included studies reflects the strict inclusion criteria applied to ensure relevance, methodological rigor, and a specific focus on elementary mathematics learning.

Table 1. *PRISMA Flow Summary*

Stage	Description	Number
Identification	Articles retrieved from databases	183
Screening	After duplicate removal	152
Eligibility	Full-text assessed	80
Included	Articles meeting criteria	8

The quality of the included studies was assessed using the Mixed Methods Appraisal Tool (MMAT) 2018 (Hong et al., 2018). The assessment focused on clarity of research questions, appropriateness of research design, data collection procedures, rigor of data analysis, consistency between findings and conclusions. Each of the eight included studies was assessed against the MMAT criteria, and the appraisal results were used to inform the credibility and interpretation of the findings. The appraisal was not used solely as a strict cutoff criterion, but rather to ensure that all included studies demonstrated acceptable methodological quality and transparency.

Data were analyzed using thematic analysis based on Braun and Clarke (2006). The analysis followed six phases:

1. Familiarization with the data
2. Generation of initial codes
3. Searching for themes

4. Reviewing themes
5. Defining and naming themes
6. Producing the report

The coding process was conducted inductively, allowing themes to emerge directly from the data rather than being predetermined. To enhance trustworthiness, the coding process involved iterative comparison across the eight included studies to ensure consistency and minimize subjective bias.

The analysis focused on identifying patterns related to how VR/AR supports the UDL principles of representation, engagement, action and expression.

The characteristics of the included studies are summarized in Table 2.

Table 2. *Summary of Included Studies*

No	Author(s) & Year	Research Purpose	Method	Main Findings
1	Lintiasri et al. (2024)	To examine the effect of AR on Grade 5 mathematics learning outcomes	Experiment	AR significantly improves students' geometry comprehension
2	Kenedi et al. (2023)	To evaluate the impact of VR on elementary students' geometric skills	Experiment	VR enhances spatial skills and increases learning motivation
3	Muspiroh et al. (2025)	To investigate AR use across regions in enhancing elementary science and math concepts	Mixed-methods	AR strengthens engagement and conceptual mastery
4	Akhmad & Priyono (2023)	To develop AR-based math learning media using the ADDIE model	R&D	AR media are feasible and increase students' interest in learning

5	Nurfitriani & Hidayat (2022)	To evaluate AR use in Indonesian elementary mathematics classrooms	Quantitative	AR enhances learning outcomes and student collaboration
6	Hsu et al. (2021)	To examine the influence of AR on students' mathematical behavior and performance	Experiment	AR increases students' self-efficacy and learning engagement
7	Rahmawati (2021)	To develop AR media for improving spatial ability using Merge Cube	R&D	AR effectively develops students' spatial visualization skills
8	Yilmaz (2016)	To examine AR in early learning environments	Experiment	AR improves motivation and learning outcomes

3. Result and Discussion

This section presents a synthesis of findings from the eight empirical studies included in the review. The analysis focuses on how Virtual Reality (VR) and Augmented Reality (AR) relate to the principles of Universal Design for Learning (UDL) in elementary mathematics learning. The thematic analysis identified four main patterns: (1) enhanced representation of mathematical concepts, (2) increased student engagement, (3) expanded opportunities for action and expression, and (4) implementation challenges. These themes are interpreted as conceptual alignments with UDL principles rather than direct empirical measurements of UDL constructs.

3.1 Strengthening Mathematical Representation Through Visual and Interactive Models

Across the eight studies, findings consistently indicate that AR and VR enhance students understanding of abstract and spatial mathematical concepts, particularly in geometry learning contexts. Lintiasri et al. (2024), Kenedi et al. (2023), and Rahmawati (2021) reported improvements in students' comprehension of three-dimensional objects, spatial relationships, and transformations through interactive visual representations. These results suggest that immersive technologies play a significant role in bridging the gap between abstract mathematical symbols and concrete understanding.

These improvements are supported by specific technological affordances such as object manipulation, rotation, zooming, and multi-perspective visualization. For example, Lintiasri et al. (2024) emphasized improvements in geometric comprehension through AR-based visualization, while Rahmawati (2021) highlighted how interactive manipulation of 3D objects strengthened spatial reasoning. In contrast, Kenedi et al. (2023) showed that VR environments contributed more strongly to immersive exploration, suggesting that AR and VR may support different cognitive processes AR emphasizing visualization clarity, while VR enhances experiential immersion.

This distinction indicates that immersive technologies do not function uniformly, but rather provide complementary affordances that influence different dimensions of mathematical understanding. However, most studies focus on short-term improvements in conceptual understanding within controlled settings. The extent to which these improvements are sustained over time or transferred to broader mathematical problem-solving contexts remains underexplored.

These findings can be interpreted as aligning with the UDL principle of multiple means of representation, as VR/AR provide alternative pathways for accessing mathematical content. In the Indonesian context, this is particularly relevant, as access to physical manipulatives is often limited. As noted by Nurfitriani and Hidayat (2022), AR-based tools can function as digital substitutes for concrete learning media. However, their effectiveness is strongly influenced by infrastructure availability and teacher readiness.

Importantly, improved representation also appears to influence engagement. Clearer visualization may reduce cognitive load and support more meaningful interaction with mathematical tasks, suggesting an interconnected relationship between representation and engagement rather than isolated effects.

3.2 Increasing Student Engagement Through Immersive and Interactive Learning

Across the reviewed studies, AR and VR are consistently associated with increased student engagement, including improvements in motivation, attention, and active participation. Evidence from Hsu et al. (2021), Kenedi et al. (2023), Muspiroh et al. (2025), and Yilmaz (2016) shows that students in immersive environments demonstrate higher levels of involvement compared to conventional classrooms.

However, different studies highlight distinct dimensions of engagement. Hsu et al. (2021) emphasized increased self-efficacy and active participation, while Muspiroh et al. (2025) reported enhanced attention and persistence across different classroom contexts. In contrast, Yilmaz (2016) highlighted the role of novelty and enjoyment in driving motivation, suggesting that initial engagement may be influenced by the newness of the technology rather than its pedagogical effectiveness.

This variation indicates that engagement is not a single construct but a multidimensional phenomenon encompassing behavioral, emotional, and cognitive components. While immersive technologies appear effective in stimulating engagement, the sustainability of these effects remains uncertain. Engagement driven by novelty may diminish over time if not supported by meaningful instructional design.

These findings align with the UDL principle of multiple means of engagement, as VR/AR create more interactive and motivating learning environments. However, most studies measure engagement using general indicators rather than UDL-specific constructs, limiting direct conclusions about UDL implementation.

Furthermore, the relationship between engagement and learning outcomes is not always linear. Increased engagement does not automatically translate into deeper conceptual understanding, suggesting that the pedagogical integration of VR/AR is a critical factor. Therefore, immersive technologies should be viewed as tools that can facilitate engagement, but not as standalone solutions.

3.3 Expanding Opportunities for Action and Expression Through Digital Manipulation

Across the included studies, AR and VR provide diverse pathways for students to express their mathematical understanding beyond traditional written or verbal formats. Rahmawati (2021) and Akhmad and Priyono (2023) consistently demonstrate that students can communicate their understanding through interaction with digital objects and visual representations. Rahmawati (2021) showed that AR-based Merge Cube activities enabled students to manipulate geometric objects independently, supporting clearer articulation of spatial relationships. Similarly, Akhmad and Priyono (2023) found that AR-based learning media allowed students to construct and modify mathematical models, enabling visual demonstration of reasoning processes.

Compared to traditional instruction, these approaches reduce reliance on linguistic expression and support multimodal communication. This is particularly beneficial for students who may struggle with conventional forms of expression, including those with diverse learning needs.

These findings align with the UDL principle of multiple means of action and expression, as learners are provided with varied ways to demonstrate understanding. However, most studies primarily report improvements in task performance rather than explicitly measuring expressive diversity. As a result, the extent to which VR/AR truly expand expressive opportunities across different learner profiles remains unclear.

This suggests that VR/AR should be understood as enabling the potential expansion of expression, rather than providing definitive evidence of inclusive expressive practices. Future research should explore how these technologies support diverse learners in demonstrating understanding across different contexts and abilities.

3.4 Challenges in Implementing VR/AR in UDL-Based Instruction

Across the reviewed studies, several recurring challenges were identified, including limited access to devices, insufficient infrastructure, and variability in teacher readiness. These constraints significantly influence the feasibility and sustainability of VR/AR integration. In the Indonesian context, these challenges are particularly pronounced. Nurfitriani and Hidayat (2022) highlighted limitations in device availability and connectivity, while Muspiroh et al. (2025) reported disparities in implementation across different regions. These findings indicate that technological access remains uneven, which may reinforce rather than reduce educational inequality.

Teacher readiness is another critical factor. Without adequate training, VR/AR are often used as supplementary tools rather than being meaningfully integrated into instructional design. This limits their alignment with UDL principles and reduces their potential impact. These challenges suggest that successful implementation requires systemic support, including professional development, infrastructure investment, and curriculum alignment. Importantly, the integration of VR/AR should not be viewed solely as a technological issue, but as a pedagogical and organizational transformation. Without such support, the benefits of immersive technologies may remain localized, short-term, and dependent on specific contexts rather than scalable across broader educational systems.

Overall, the findings suggest that VR and AR have strong potential to support inclusive mathematics learning, particularly in enhancing representation, increasing engagement, and expanding opportunities for expression. However, these effects should be understood as conceptual alignments with UDL principles, rather than direct empirical validation. Importantly, the findings indicate that VR/AR function not only as technological tools but as mediating structures that reshape how learners' access, engage with, and express mathematical knowledge. At the same time, implementation challenges highlight the importance of contextual factors such as infrastructure, teacher readiness, and policy support.

These findings suggest that the effectiveness of VR/AR is not inherent in the technology itself, but emerges from the interaction between technology, pedagogy, and context. Therefore, integrating VR/AR within UDL requires not only technological innovation but also careful pedagogical design and systemic support to ensure sustainable and equitable implementation.

4. Conclusion

The findings of this review indicate that Virtual Reality (VR) and Augmented Reality (AR) have strong potential to support accessible mathematics instruction in elementary schools when aligned with Universal Design for Learning (UDL). Immersive technologies enhance conceptual understanding by transforming abstract ideas into interactive visual representations, while also increasing student motivation, attention, and participation. In addition, VR/AR provide diverse ways for learners to express understanding through digital and multimodal interaction.

From a practical perspective, VR/AR can be used as complementary tools to support diverse learners, particularly in visualizing mathematical concepts and enabling interactive exploration. However, effective implementation depends on meaningful integration with instructional design, rather than using technology as an isolated add-on. Despite these benefits, challenges such as limited device access, uneven infrastructure, and teacher readiness remain significant. Addressing these issues requires sustained professional development, institutional support, and alignment with curriculum practices.

Overall, VR/AR can enhance accessibility and participation in elementary mathematics learning when supported by appropriate pedagogical and contextual conditions. Future research should focus on long-term implementation, diverse educational contexts especially in Indonesia and the role of teacher professional development in sustaining effective integration.

5. Acknowledgments

The author expresses sincere appreciation to the faculty members and colleagues who provided valuable guidance during the preparation of this manuscript. Gratitude is also extended to the institutions that facilitated access to research databases and digital resources essential for conducting the literature review. Their support greatly contributed to the completion of this study.

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