Indonesian Journal of Education & Mathematical Science
Vol. 7, No. 2, Mei 2026, pp. 149~160
ISSN: 2721-3838, DOI: 10.30596/ijems.v7i2.29380

Geometry Learning through Extended Reality (XR): A Mini Review of Its Impacts, Implementation Challenges, and Future Developments

Nur Riski Hasanah[1], Turmudi[2], Dadang Juandi[3]
[1,2,3]Department of Mathematics Education, Universitas Pendidikan Indonesia, Bandung, Indonesia
[1]nurriskihasanah@upi.edu, [2]turmudi@upi.edu, [3]dadang.juandi@upi.edu

ABSTRACT

Extended Reality (XR) which includes AR, VR, MR, has become one of the important innovations in the development of mathematics learning media, especially in the field of geometry. This review aims to analyze the impact, implementation challenges, and future development directions of XR in geometry learning. A PRISMA-based systematic review was conducted with thematic analysis of literature from reputable international journals. The results of the study show that XR improves the effectiveness of learning and spatial thinking skills, student engagement, and learning motivation through interactive visualization and immersive learning experiences. However, negative impacts that need to be considered, include the dependence on technology, physiological and cognitive disorders, and heightened distraction that affects performance. Implementation challenges include limited infrastructure, teacher readiness, device access, costs, appropriate pedagogical design, and curriculum support for optimal XR integration. Future developments suggest that XR holds strong transformative potential through integration with artificial intelligence (AI), adaptive learning systems, and educational metaverse environments. This study highlights the need for structured XR integration strategies and further research on long-term effectiveness and appropriate XR-based pedagogical design in mathematics learning, particularly geometry.

Keywords: augmented reality, extended reality, future developments, geometry learning, impacts and challenges

Corresponding Author:
Turmudi,
Department of Mathematics Education,
Universitas Pendidikan Indonesia,
Jl. Dr. Setiabudi No.229, Isola, Kec. Sukasari, Kota Bandung, Jawa Barat 40154, Indonesia.
Email Penulis

1. INTRODUCTION

Difficulties in learning geometry remain a persistent challenge in mathematics education, particularly in understanding three-dimensional (3D) objects and their spatial relationships. Many students struggle to visualize 3D structures, interpret their components, and relate different geometric elements within space, largely due to limitations in spatial reasoning skills (Chivai et al., 2024; Fujita et al., 2020, 2022; Hasanah et al., 2025; Jablonski & Ludwig, 2023; Lowrie & Logan, 2023). These challenges often lead to superficial understanding, where students rely on memorizing formulas rather than developing meaningful conceptual knowledge of volume, surface area, cross-sections, and transformations.

A key issue underlying these difficulties is the continued reliance on two-dimensional (2D) representations in geometry instruction. In many classrooms, geometric concepts are introduced through static images, diagrams, and textbook-based models, which require students to mentally reconstruct three-dimensional forms (Ng et al., 2020; Sarkar et al., 2020). Two-dimensional representations require students to mentally reconstruct three-dimensional forms, a process that places a high cognitive load on learners with limited spatial ability. Consequently, students may resort to memorizing formulas rather than developing meaningful conceptual understanding, which limits their ability to transfer knowledge to new or unfamiliar geometric problems.

In this context, Extended Reality (XR) technologies, comprising Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), offer promising alternatives for enhancing geometry learning. XR technologies allow students to interact with geometric objects in more dynamic, interactive, and immersive ways, enabling them to observe, manipulate, and explore three-dimensional forms directly within a virtual or augmented environment (Simonetti et al., 2020; Su et al., 2022). Through XR-based learning environments, abstract geometric concepts can be transformed into concrete visual experiences, helping students bridge the gap between symbolic representations and spatial understanding.

The development and application of XR in mathematics education have progressed rapidly in recent years. Research indicates that XR enables learners to physically interact with physical–virtual

Indonesian Journal of Education & Mathematical Science
Vol. 7, No. 2, Mei 2026, pp. 149~160
ISSN: 2721-3838, DOI: 10.30596/ijems.v7i2.29380

objects or visualize three-dimensional objects that can be rotated, zoomed, and examined from multiple perspectives in real time (Anwar et al., 2025; Jagatheesaperumal et al., 2024; Shaghaghian et al., 2022). Such immersive interactions support active learning and reduce cognitive load by externalizing spatial information, thereby allowing students to focus more on conceptual reasoning rather than mental reconstruction. This immersive experience plays a crucial role in strengthening students' spatial awareness and fostering deeper understanding of geometric relationships.

Among XR technologies, Augmented Reality (AR) has gained particular attention due to its ability to integrate virtual objects into real-world contexts without isolating learners from their physical environment. Studies have shown that AR can enrich learning experiences by increasing engagement, motivation, and conceptual clarity, especially in geometry learning where visualization is essential (Gao et al., 2023; Lampropoulos et al., 2022). By overlaying virtual geometric models onto physical spaces, AR allows students to connect mathematical concepts with tangible experiences, making learning more meaningful and accessible. Therefore, XR, particularly AR, holds significant potential as an instructional medium for geometry education. The continuum and relationships among XR components are illustrated in Figure 1.

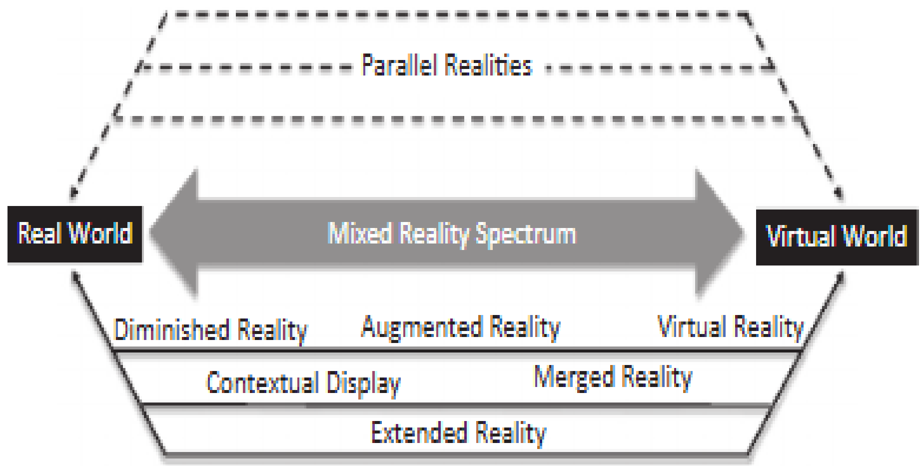

Fig. 1. Mixed Reality Spectrum from Real to Virtual World in Extended Reality (XR) Framework. Source: Adapted from (Kress & Chatterjee, 2021)

Figure 1 illustrates the Mixed Reality Spectrum, which represents a continuum showing the gradual transition from the real world to the fully virtual world through various forms of digital reality collectively referred to as Extended Reality (XR). Along this spectrum, technologies differ in the extent to which digital elements are integrated into the physical environment and the level of user interaction they afford. At one end of the spectrum is the real environment with minimal digital augmentation, such as simple overlays of information, while at the other end lies fully immersive virtual environments that completely replace the real world. Between these extremes are Augmented Reality (AR) and Mixed Reality (MR), which blend real and virtual elements in varying proportions. This spectrum highlights that XR is not a single technology, but rather a range of technologies that support different instructional goals by enabling learners to interact with digital representations in contextually meaningful ways (Kress & Chatterjee, 2021). In educational settings, particularly in geometry learning, this gradual integration allows educators to select appropriate XR modalities that align with students' cognitive readiness, learning objectives, and instructional design.

Although XR offers many advantages in education, particularly in enhancing visualization and interactivity, its use in geometry learning also presents several challenges that need careful consideration. A number of studies have reported negative physiological and cognitive effects associated with prolonged XR use, such as cybersickness, which includes symptoms like dizziness, nausea, and visual discomfort (Fan et al., 2023; Oh & Son, 2022; Spilka & SpilkaIs, 2023). These effects are often caused by a mismatch between users' physical movements and their perceived motion in virtual environments, leading to sensory conflicts that reduce comfort and learning efficiency. From a cognitive perspective, unstructured or poorly designed XR experiences may distract students from conceptual understanding, as learners may focus excessively on visual effects, animations, or interactivity rather than on underlying mathematical ideas (Pérez-Juárez et al., 2023). While immersive visuals can initially increase motivation, overly complex or visually dense XR environments risk overwhelming students' cognitive load. Therefore, XR-based learning environments must be carefully balanced with clear instructional guidance, scaffolding, and reflection activities to ensure that technology supports, rather than hinders, meaningful mathematical learning. Furthermore, without appropriate pedagogical integration, XR may encourage superficial engagement with content and foster dependency on technology rather than promoting deep cognitive processing and reflective thinking, which are essential aspects of meaningful learning (Hasanah et al., 2025).

Several previous studies have examined the positive impacts of XR use in mathematics education, particularly in the domain of geometry learning, where spatial visualization plays a significant role. Research has consistently shown that Augmented Reality (AR) can support students' understanding of three-dimensional geometric objects by allowing them to visualize, manipulate, and explore shapes that are difficult to represent adequately using static images or physical models alone (Flores-Bascuñana et al., 2019; Park & Lee, 2020; Tarng et al., 2024; Thamrongrat & Law, 2019; Yaniawati et al., 2023). These studies emphasize, however, that the effectiveness of AR depends heavily on its alignment with curriculum goals and pedagogical strategies. Similarly, studies on Virtual Reality (VR) have found that immersive environments can enrich learning experiences by providing students with a strong sense of presence and spatial awareness, which can enhance conceptual understanding. At the same time, excessive exposure to VR environments has been associated with mental fatigue and reduced learning efficiency when students spend too long in fully immersive settings. Moreover, although the use of XR in education continues to expand, many existing review studies focus primarily on short-term learning gains or immediate positive outcomes (Bulut & Borromeo F, 2023; Huang & Tseng, 2025; Mouali et al., 2024). As a result, the potential negative impacts and long-term implications of XR use in mathematics education remain underexplored. While technological advancements in XR are expected to create new educational opportunities, systematic investigations into prospects and sustainable implementation in geometry learning are still limited.

Although numerous studies have discussed the benefits of XR in geometry learning, few have critically examined the potential negative impacts and long-term challenges associated with its use. Most existing review studies tend to highlight the technical capabilities and pedagogical advantages of XR, such as improved visualization and increased student engagement, while paying less attention to risks, including cognitive overload, reduced conceptual focus, and long-term dependency on immersive technologies. In addition, limited attention has been given to how XR technologies might evolve in the future and how such developments could influence geometry learning over time. Therefore, this study aims to address these gaps by analyzing both the positive and negative impacts of XR in geometry learning, as well as the practical and pedagogical challenges involved in its implementation. The novelty of this study lies in its focus on integrating both the benefits and potential limitations of XR within a single analysis, while also considering the longer-term implications of XR use for geometry learning, which have received limited attention in previous studies.

Furthermore, this article seeks to project future directions for XR development that are more pedagogically integrated, sustainable, and contextually appropriate. By doing so, this study is expected to serve as a valuable reference for educators, researchers, and technology developers who seek to optimize the use of XR in mathematics education while carefully considering both its benefits and potential risks.

2. RESEARCH METHOD

This review was conducted based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, which are widely recognized as a rigorous framework for conducting systematic literature reviews in educational and scientific research. Although this study did not involve a quantitative meta-analysis, the PRISMA framework was adopted to ensure transparency, consistency, and traceability throughout the process of identifying, screening, selecting, and analyzing relevant studies. The use of PRISMA helps minimize bias and provides a clear methodological pathway that allows other researchers to replicate or evaluate the review process.

The literature search was conducted using several major and reputable electronic databases, including Scopus, SpringerLink, ScienceDirect, IEEE Xplore, Emerald. These databases were selected to ensure broad coverage of high-quality peer-reviewed publications in the fields of education, technology, and mathematics. A comprehensive keyword strategy was employed by combining terms such as “Geometry Learning" or "Geometry Teaching" or “Geometry Education” and "Extended Reality" or "XR" or "Augmented Reality" or “AR” or "Virtual Reality" or “VR” or "Mixed Reality" or “MR” and “impact” or “effect” or “influence” or “implication” or “potential development” or “prospective development” or “future development” or “future directions” or “challenges” or “difficulties” or “obstacles” or “constraint” or “limitation”. This combination of keywords was intended to capture not only studies focusing on learning outcomes, but also those discussing implementation issues and future directions of XR in educational contexts.

The search was limited to articles published between 2016 and 2026 to reflect the rapid development of XR technologies and their recent adoption in education. Only articles written in English were included to maintain consistency and accessibility in analysis. The inclusion criteria encompassed empirical studies employing quantitative, qualitative, or mixed-method approaches, as well as systematic or narrative literature reviews that explicitly addressed the use of XR in geometry learning, mathematics education, or closely related instructional contexts. Furthermore, the selected studies were required to discuss at least one of the following aspects: the impact of XR on learning, the challenges associated with its implementation, or the prospective development of XR technologies in education.

Studies were excluded if they focused on XR applications outside educational settings, such as medical training, industrial simulation, or entertainment, without clear relevance to learning or pedagogy. In addition, articles that had not undergone a peer-review process, such as unpublished manuscripts or non-academic reports, were excluded to ensure the reliability and academic quality of the reviewed literature.

The article selection procedure was conducted in three systematic stages. The first stage involved initial identification based on keyword search results across all databases. In the second stage, titles and abstracts were screened to assess their relevance to the research focus. The final stage consisted of full-text reading to determine the suitability of each article based on its alignment with the research objectives and inclusion criteria. After selection, data from the included studies were analyzed using thematic analysis. This process involved categorizing and synthesizing findings into key themes related to the impacts, challenges, and future developments of XR in geometry learning, enabling a structured and comprehensive interpretation of existing research trends. The flow of the study is presented in Figure 2.

Indonesian Journal of Education & Mathematical Science
Vol. 7, No. 2, Mei 2026, pp. 149~160
ISSN: 2721-3838, DOI: 10.30596/ijems.v7i2.29380

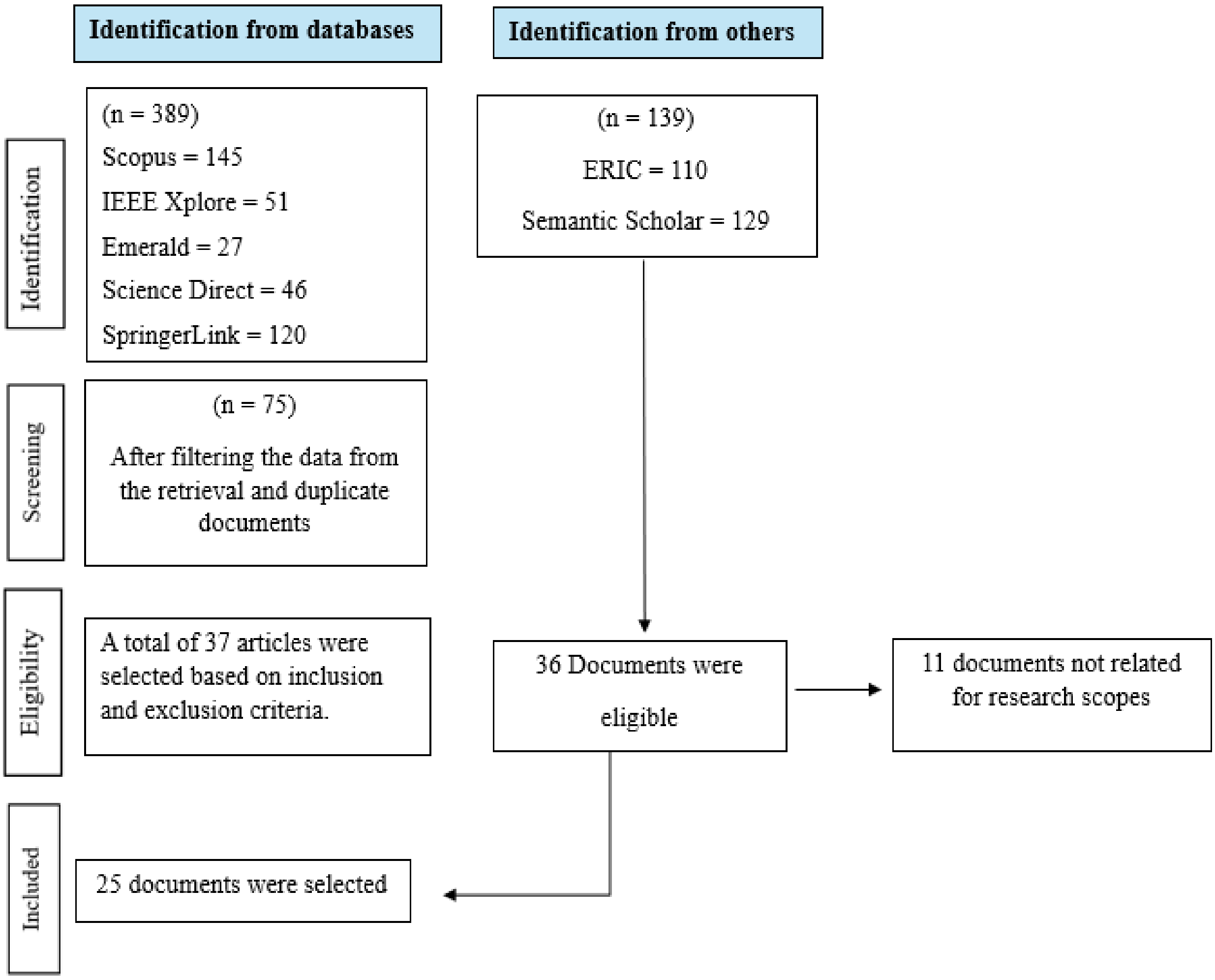

Fig. 2. The flow of the study selection and analysis process

3. RESULTS AND DISCUSSION

A. Positive Impacts of Using XR in Geometry Learning

The use of Extended Reality (XR) in geometry learning has been shown to have a significant positive impact on learning effectiveness, particularly in helping students understand abstract geometric concepts that are often difficult to grasp through conventional instruction. Technologies such as Augmented Reality (AR) and Virtual Reality (VR) enable students to visualize three-dimensional geometric objects interactively, allowing them to explore shapes, surfaces, and spatial relationships dynamically rather than passively observing static representations. This interactive visualization helps bridge the gap between abstract mathematical symbols and concrete spatial understanding, which is often a challenge in traditional geometry instruction(Arvanitaki & Zaranis, 2020; Demitriadou et al., 2020; Ding et al., 2024; Tarng et al., 2024).

Empirical studies have consistently reported that students who learn geometry using AR experience significantly higher levels of conceptual understanding compared to those taught using traditional methods. For example, experimental research has shown that AR-based instruction enhances students' ability to identify geometric properties, visualize transformations, and understand relationships among three-dimensional objects (Gargrish et al., 2021; İbili et al., 2020; Rossano et al., 2020) This improvement is largely attributed to the ability of AR to overlay digital geometric models onto real-world environments, enabling students to observe and manipulate objects from multiple perspectives in real time.

Similarly, VR technology supports geometry learning by offering immersive environments in which students can interact intuitively with abstract concepts, complex structures, and dynamic geometric processes. Through immersive visualization, students are able to experience geometric ideas such as rotation, scaling, and spatial transformation in a more embodied way, which supports deeper cognitive processing (Wong et al., 2024). Such immersive experiences allow learners to construct meaning through exploration and interaction, aligning with constructivist learning principles.

In addition to enhancing conceptual understanding, XR technologies have been shown to increase student motivation and engagement. The immersive and interactive nature of XR creates a more stimulating learning environment that captures students' attention and encourages active participation. Several studies indicate that students demonstrate higher levels of interest, curiosity, and persistence when learning geometry through XR-based activities compared to traditional instruction (Cárdenas-Sainz et al., 2023; Hmoud et al., 2023; Taborda et al., 2025). This heightened engagement is particularly important in geometry learning, where students often experience anxiety or lack of confidence due to the abstract nature of the subject.

Furthermore, XR has been found to significantly support the development of spatial thinking skills, which are central to geometry learning. Skills such as mental rotation, spatial visualization, shape projection, and understanding spatial relationships between geometric elements can be strengthened through direct interaction with three-dimensional models (Baumgartner et al., 2022; Darwish et al., 2023) By allowing students to manipulate objects in three dimensions, XR helps learners develop a more accurate and flexible mental representation of geometric forms, thereby enhancing their spatial reasoning abilities (Cunha et al., 2024).

Through interactive simulations, XR transforms geometry learning from an abstract and symbolic process into a more concrete and experiential activity. Students can experiment with geometric objects, observe cause-and-effect relationships, and test hypotheses through virtual manipulation, which supports inquiry-based and experiential learning approaches (Gittinger & Wiesche, 2024). As a result, students are better able to connect geometric concepts to real-world contexts, such as architecture, engineering, and everyday Social problem-solving (Chonchaiya & Srithammee, 2025; Walkington et al., 2024; Zhang et al., 2024).

Moreover, XR-based geometry learning often incorporates gamified and exploration-oriented elements that further enhance student motivation. Game-like features such as challenges, levels, and immediate feedback encourage students to engage more deeply with the learning material and sustain their interest over time (Fidan & Tuncel, 2019; Lampropoulos et al., 2022). These elements support both intrinsic motivation and self-directed learning, which are important factors in successful mathematics education.

Research also suggests that XR supports active learning by accommodating different learning styles, particularly visual and kinesthetic learners. The combination of visual immersion and physical interaction enables students to actively construct knowledge rather than passively receive information (Barbu et al., 2025; Iqbal & Campbell, 2023b, 2023a) Additionally, XR allows learners to progress at their own pace, revisit concepts as needed, and engage collaboratively with peers, thereby supporting personalized and inclusive learning environments.

However, while these findings confirm the effectiveness of XR in enhancing geometry learning, they also reflect a dominant focus in existing literature on positive outcomes, with limited attention to potential drawbacks and long-term implications.

B. Negative Impacts and Challenges of XR Implementation

In contrast to the positive emphasis in previous studies, this section highlights the less explored negative impacts and challenges associated with XR implementation. Although Extended Reality (XR) has considerable potential to enhance learning effectiveness, particularly in geometry education, numerous studies have highlighted several negative impacts that must be carefully considered. One of the most frequently reported issues relates to physiological and cognitive effects experienced by users, especially when XR technologies are used intensively or over extended periods. Research indicates that XR usage may trigger anxiety and stress among teachers, particularly when they feel unprepared to operate or integrate the technology effectively into classroom instruction (Fernández-Batanero et al., 2021). In younger learners, XR exposure has also been linked to changes in emotional responses and behavioral patterns, which may interfere with sustained attention and learning regulation (Ventouris et al., 2021). Additionally, XR environments can become a source of distraction, as students may focus more on visual effects and interactive features rather than on underlying mathematical concepts, ultimately affecting learning performance (Pérez-Juárez et al., 2023).

Beyond these immediate effects, there is growing concern regarding over-reliance on technology in learning contexts. When XR tools are used excessively without appropriate pedagogical scaffolding, students may become dependent on digital visualization, reducing their ability to engage in mental imagery, abstract reasoning, and independent critical thinking (Abbas et al., 2024; Gerlich, 2025). In geometry learning, this dependency can be particularly problematic, as spatial reasoning skills ideally involve the ability to mentally manipulate shapes without constant external visual support. Furthermore, the rapid expansion of XR applications, especially Augmented Reality (AR) and Virtual Reality (VR), has not always been accompanied by sufficient pedagogical frameworks to guide effective integration into existing curricula. As a result, XR use may remain superficial or entertainment-oriented rather than conceptually meaningful. In addition, multiple studies have reported physical side effects such as eye strain, dizziness, balance disorders, and cybersickness, including nausea and disorientation, especially with prolonged VR use (Oh & Son, 2022; Spilka & SpilkaIs, 2023; Fan et al., 2023). These issues highlight the importance of regulating XR use to ensure that its benefits do not come at the expense of learners' physical well-being and cognitive focus.

In addition to individual-level impacts, systemic challenges significantly affect the implementation of XR in educational settings. One major barrier is the limitation of infrastructure, accessibility of devices, and financial cost(Walkington et al., 2024). XR technologies often require expensive hardware such as VR headsets, MR devices, motion sensors, and compatible computing systems, making them difficult to adopt widely, particularly in under-resourced schools and developing regions (Lindner et al., 2019). This situation risks exacerbating the digital divide, where only certain institutions can benefit from advanced educational technologies, potentially widening inequalities in educational quality and learning opportunities (Assefa et al., 2025). Empirical findings by (Radianti et al., 2020) further demonstrate that many schools face significant obstacles in acquiring and maintaining XR equipment, while recent studies confirm that these challenges remain prevalent (Wang et al., 2024).

Another critical challenge involves the readiness and professional competence of teachers. Effective integration of XR requires not only access to technology but also sufficient pedagogical and technological expertise. Many educators lack formal training or prior experience with XR, limiting their confidence and ability to design meaningful XR-based learning activities. This issue aligns with findings by Hasanah et al. (2024), who identified gaps in teachers' Technological Knowledge within the TPACK framework, often caused by limited or inadequate professional development opportunities. Without proper training, XR may be underutilized or misused, reducing its potential impact on learning outcomes. Therefore, continuous professional development programs, technical support, and pedagogical guidance are essential to help teachers integrate XR thoughtfully and effectively into classroom practice (Doerner & Horst, 2022; Nikou et al., 2024; Schwaiger et al., 2024). Addressing these challenges is crucial to ensuring that XR adoption in geometry learning is both sustainable and pedagogically sound.

C. Future Developments of XR in Geometry Learning

In recent years, the use of Extended Reality (XR) technology in education has increasingly shifted toward the development of more adaptive, intelligent, and integrated learning systems (Hanid et al., 2025; Jamah et al., 2022; Wong et al., 2024). This shift is particularly important in addressing the limitations identified in previous studies, which have focused on short-term benefits while overlooking long-term sustainability, potential risks, and future implementation challenges of XR in geometry learning. This reflects the growing recognition that learning technologies should not merely function as visualization tools, but also respond dynamically to learners' cognitive needs, learning pace, and conceptual difficulties. In geometry learning, where students often struggle with abstract spatial relationships, adaptive XR systems offer the possibility of providing immediate feedback, scaffolding, and differentiated learning pathways. By adjusting visual complexity, interaction levels, or learning sequences, XR environments can better accommodate diverse learners and promote deeper conceptual understanding.

One promising direction in XR development is its integration with artificial intelligence (AI). The combination of XR and AI enables the creation of immersive learning environments that are not

Vol. 7, No. 2, Mei 2026, pp. 149~160
ISSN: 2721-3838, DOI: 10.30596/ijems.v7i2.29380

only interactive but also personalized and responsive to individual student profiles (Alkaeed et al., 2024; De Pisapia, 2024; Memarian & Doleck, 2024; Zhou & Divekar, 2025). AI-driven XR systems can analyze students' interaction patterns, detect misconceptions, and adapt instructional content accordingly. In geometry learning, this means that students may receive tailored visual representations, adaptive problem sets, or targeted prompts that support their spatial reasoning processes. Such personalization has the potential to enhance learning efficiency and reduce cognitive overload, particularly for students with lower spatial abilities.

Furthermore, XR technologies are increasingly being integrated into cloud-based learning platforms and mobile learning environments, expanding access to immersive geometry learning beyond physical classrooms (Meccawy, 2022; Theodoropoulos et al., 2022). This development opens opportunities for remote and hybrid learning models where students can engage with three-dimensional geometric objects anytime and anywhere. Through mobile AR applications or cloud-based VR systems, students can explore geometric concepts collaboratively, even when learning from various locations. This flexibility is especially valuable for addressing educational inequities, as it allows broader access to high-quality learning experiences without requiring advanced physical infrastructure at every school.

Looking ahead, XR is also expected to play a significant role in the emergence of educational metaverses. In these virtual environments, geometry learning can take place within shared, persistent, and interactive three-dimensional spaces that support real-time collaboration (Wang et al., 2024). Within a metaverse-based learning context, students can jointly manipulate geometric objects, discuss spatial relationships, and solve problems collaboratively, thereby fostering social interaction and collective knowledge construction. Such environments align well with constructivist and socio-cultural learning theories, which emphasize learning as an active and collaborative process.

Recent studies further highlight that XR will become an important catalyst in STEM education, particularly in subject areas that demand complex spatial visualization and multidimensional reasoning (Hasanah et al., 2024). Geometry, as a foundational domain within STEM, stands to benefit significantly from XR-based innovations that enable students to visualize, manipulate, and experiment with spatial forms that are otherwise difficult to represent through traditional two-dimensional media. However, the successful adoption of XR in geometry learning requires careful alignment with pedagogical principles, learning objectives, and curriculum standards.

Despite its promising prospects, XR adoption must be accompanied by systematic teacher training and thoughtful curriculum integration to ensure that it functions as an effective pedagogical solution rather than merely a technological novelty (Caena & Redecker, 2019; Haleem et al., 2022). Teachers need sufficient technological, pedagogical, and content knowledge to design meaningful XR-supported learning activities and to guide students in reflective and purposeful use of the technology. In addition, considerations related to students' cognitive readiness, ethical use of technology, and balanced screen time are essential to maximize learning benefits while minimizing potential risks (Szymkowiak et al., 2021).

In the future, XR development in education is likely to be increasingly intertwined with other advanced technologies such as artificial intelligence and big data analytics, enabling the creation of highly adaptive and data-driven learning ecosystems. AI-powered XR environments may support real-time learning analytics, predictive feedback, and continuous assessment, allowing educators to make informed instructional decisions. Moreover, the growing use of Mixed Reality (MR), which blends real-world contexts with virtual elements, offers particularly strong potential for geometry learning by providing contextualized and application-oriented experiences. MR allows students to connect abstract geometric concepts directly with physical environments, thereby strengthening conceptual transfer and real-world relevance.

Nevertheless, to realize the full potential of XR in geometry education, a coordinated and collaborative approach involving technology developers, educators, researchers, and policymakers is essential (Barbu et al., 2025). Decisions related to content selection, instructional design, software development, hardware solutions, and classroom implementation must be made holistically and contextually (Kluge et al., 2023). In addition, long-term empirical research is needed to examine the sustained effectiveness, cognitive impact, and pedagogical value of XR-supported geometry learning. Such efforts are crucial to ensure that XR technologies contribute meaningfully and sustainably to the future of mathematics education.

Vol. 7, No. 2, Mei 2026, pp. 149~160
ISSN: 2721-3838, DOI: 10.30596/ijems.v7i2.29380

Overall, the findings indicate that XR provides substantial pedagogical benefits in geometry learning by enhancing conceptual understanding, spatial reasoning, motivation, and learner engagement. However, in contrast to prior studies that emphasize positive outcomes, this review also reveals several critical limitations and challenges associated with XR use. These include the risk of cognitive overload, potential distraction from core mathematical concepts due to excessive visualization and reported physiological effects such as discomfort and fatigue during prolonged use.

These findings directly address the identified research gap by demonstrating that XR in geometry learning is not exclusively beneficial but presents a complex interplay between pedagogical affordances and potential constraints. While XR supports constructivist and student-centred learning environments, its effectiveness is highly dependent on careful instructional design, scaffolding, and alignment with learning objectives.

Furthermore, the results extend beyond short-term learning outcomes by highlighting concerns related to sustainability and long-term implementation, including the need to prevent overreliance on technology and to ensure that students maintain deep conceptual understanding and reflective thinking. This underscores the importance of integrating XR thoughtfully within pedagogical frameworks rather than treating it as a standalone technological solution. Therefore, the findings not only confirm the strong potential of XR to support contextual and student-centred mathematics learning, but also provide a more balanced perspective that incorporates its limitations, challenges, and future implications—areas that have been underexplored in previous research.

4. CONCLUSION

The use of Extended Reality (XR), encompassing Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR), demonstrates substantial potential in enhancing the effectiveness of geometry learning within mathematics education. The findings of this review indicate that XR-based learning environments contribute positively to the development of students' spatial thinking abilities, including mental rotation, spatial visualization, and the understanding of relationships among three-dimensional geometric objects. By enabling learners to interact directly with virtual geometric representations, XR facilitates deeper conceptual understanding that is often difficult to achieve through conventional two-dimensional instructional media such as textbooks or static diagrams. In addition, the immersive and interactive characteristics of XR have been shown to increase student engagement, learning motivation, and active participation, particularly among learners who benefit from visual and kinesthetic learning modalities.

Despite these promising benefits, the implementation of XR in geometry learning is not without challenges and potential negative impacts. This study highlights several critical concerns, including technical and financial constraints related to the procurement and maintenance of XR devices, such as head-mounted displays and supporting hardware. Moreover, prolonged or unregulated use of XR technologies may lead to negative physiological and cognitive effects, including eye strain, dizziness, cybersickness, and cognitive overload, which can ultimately reduce learning effectiveness. From a pedagogical perspective, XR may also become a source of distraction if instructional design does not adequately align immersive features with clear learning objectives. Without appropriate scaffolding and guidance, students may focus more on visual novelty rather than on meaningful conceptual understanding.

Another significant issue identified in this review is the unequal access to XR technologies across different educational contexts. Institutions located in under-resourced or developing regions often face limitations in infrastructure, internet connectivity, and teacher readiness, which can widen existing educational disparities. As a result, while XR has the potential to democratize access to high-quality visualization-based learning, its uneven implementation may paradoxically exacerbate inequalities in technology-based education if not accompanied by inclusive policies and support systems.

Looking forward, the future development of XR in geometry learning is expected to move toward greater integration with advanced technologies such as artificial intelligence (AI), adaptive learning systems, big data analytics, and educational metaverses. These technological advancements offer opportunities to create more personalized, responsive, and data-driven learning experiences that adapt to individual students' needs, learning pace, and cognitive profiles. Furthermore, the emergence of collaborative virtual environments within educational metaverses has the potential to transform geometry learning into a shared, interactive, and socially mediated experience that transcends physical and geographical boundaries.

Considering these developments, it is essential for educators, educational technology developers, and policy makers to adopt a structured, inclusive, and sustainable approach to XR integration. Teacher professional development, curriculum alignment, and pedagogically grounded content design are critical to ensuring that XR functions not merely as a technological novelty, but as an effective instructional tool that supports meaningful learning. Finally, this study underscores the need for further longitudinal and empirical research examining the long-term cognitive, pedagogical, and socio-emotional impacts of XR use in geometry learning. Such research will be instrumental in strengthening both the theoretical foundations and practical applications of XR in mathematics education, particularly in fostering deeper conceptual understanding and equitable learning opportunities in geometry.

ACKNOWLEDGEMENTS

The authors would like to express their deepest gratitude to all individuals and institutions that have contributed to the completion of this research, both directly and indirectly. This study would not have been possible without the academic support and collaborative environment provided by colleagues and reviewers who offered valuable insights throughout the research and writing process. Special appreciation is extended to the Ministry of Higher Education, Science, and Technology (Kemendiktisaintek) of the Republic of Indonesia for its generous support through the PMDSU (Pendidikan Magister Menuju Doktor untuk Sarjana Unggul) Scholarship. This scholarship program plays a crucial role in fostering high-quality doctoral research by enabling early-career scholars to engage in advanced academic training and international research exposure. The financial and institutional support provided through PMDSU has significantly contributed to the continuity, focus, and academic rigor of this research.

REFERENCES

Alkaeed, M., Qayyum, A., & Qadir, J. (2024). Privacy preservation in Artificial Intelligence and Extended Reality (AI-XR) metaverses: A survey. *Journal of Network and Computer Applications*, 103989.

Anwar, M. S., Yang, J., Frnda, J., Choi, A., Baghaei, N., & Ali, M. (2025). Metaverse and XR for cultural heritage education: applications, standards, architecture, and technological insights for enhanced immersive experience. *Virtual Reality*, *29*(2), 51.

Arvanitaki, M., & Zaranis, N. (2020). The use of ICT in teaching geometry in primary school. *Education and Information Technologies*, *25*(6), 5003–5016.

Assefa, Y., Gebremeskel, M. M., Moges, B. T., Tilwani, S. A., & Azmera, Y. A. (2025). Rethinking the digital divide and associated educational in (equity) in higher education in the context of developing countries: the social justice perspective. *The International Journal of Information and Learning Technology*, *42*(1), 15–32.

Barbu, M., Iordache, D.-D., Petre, I., Barbu, D.-C., & Băjenaru, L. (2025). Framework Design for Reinforcing the Potential of XR Technologies in Transforming Inclusive Education. *Applied Sciences*, *15*(3), 1484.

Baumgartner, E., Ferdig, R. E., & Gandolfi, E. (2022). Exploring the impact of extended reality (XR) on spatial reasoning of elementary students. *TechTrends*, *66*(5), 825–836.

Bulut, M., & Borromeo F, R. (2023). A systematic literature review on augmented reality in mathematics education. *European Journal of Science and Mathematics Education*, *11*(3), 556–572.

Caena, F., & Redecker, C. (2019). Aligning teacher competence frameworks to 21st century challenges: The case for the European Digital Competence Framework for Educators (Digcompedu). *European Journal of Education*, *54*(3), 356–369.

Cárdenas-Sainz, B. A., Barrón-Estrada, M. L., Zatarain-Cabada, R., & Chavez-Echeagaray, M. E. (2023). Evaluation of eXtended reality (XR) technology on motivation for learning physics among students in Mexican schools. *Computers & Education: X Reality*, *3*, 100036.

Chivai, C. H., Soares, A. A., & Catarino, P. (2024). Promotion of spatial visualization with GeoGebra and Qubism 3D software. *Educação e Pesquisa*, *50*, e275201.

Chonchaiya, R., & Srithammee, N. (2025). Augmented Reality as a Tool for Enhancing Geometry Learning and Improving Mathematical Understanding. *ECTI Transactions on Computer and Information Technology (ECTI-CIT)*, *19*(2), 350–363.

Cunha, C. R., Moreira, A., Coelho, S., Mendonça, V., & Gomes, J. P. (2024). Converging extended reality and Machine Learning to improve the lecturing of geometry in basic education. *Journal of Engineering Research*.

Darwish, M., Kamel, S., & Assem, A. (2023). Extended reality for enhancing spatial ability in architecture design education. *Ain Shams Engineering Journal*, *14*(6), 102104.

De Pisapia, N. (2024). Understanding consciousness in the age of AI and XR: Altered states, emerging realities, and the digital self. In *Mind, Body, and Digital Brains* (pp. 81–93). Springer.

Demitriadou, E., Stavroulia, K.-E., & Lanitis, A. (2020). Comparative evaluation of virtual and augmented reality for teaching mathematics in primary education. *Education and Information Technologies*, *25*(1), 381–401.

Ding, J., Hong, Z., & Yu, M. (2024). The Application and Effects of Augmented Reality in Geometry Learning. *Lecture Notes in Education Psychology and Public Media*, *74*, 34–42.

Doerner, R., & Horst, R. (2022). Overcoming challenges when teaching hands-on courses about Virtual Reality and Augmented Reality: Methods, techniques and best practice. *Graphics and Visual Computing*, *6*, 200037.

Fan, L., Wang, J., Li, Q., Song, Z., Dong, J., Bao, F., & Wang, X. (2023). Eye movement characteristics and visual fatigue assessment of virtual reality games with different interaction modes. *Frontiers in Neuroscience*, *17*, 1173127.

Fernández-Batanero, J.-M., Román-Graván, P., Reyes-Rebollo, M.-M., & Montenegro-Rueda, M. (2021). Impact of educational technology on teacher stress and anxiety: A literature review. *International Journal of Environmental Research and Public Health*, *18*(2), 548.

Fidan, M., & Tuncel, M. (2019). Integrating augmented reality into problem based learning: The effects on learning achievement and attitude in physics education. *Computers & Education*, *142*, 103635.

Flores-Bascuñana, M., Diago, P. D., Villena-Taranilla, R., & Yáñez, D. F. (2019). On augmented reality for the learning of 3D-geometric contents: A preliminary exploratory study with 6-grade primary students. *Education Sciences*, *10*(1), 4.

Fujita, T., Kondo, Y., Kumakura, H., Kunimune, S., & Jones, K. (2020). Spatial reasoning skills about 2D representations of 3D geometrical shapes in grades 4 to 9. *Mathematics Education Research Journal*, *32*, 235–255.

Fujita, T., Kondo, Y., Kumakura, H., Miawaki, S., Kunimune, S., & Shojima, K. (2022). Identifying Japanese students' core spatial reasoning skills by solving 3D geometry problems: An exploration. *Asian Journal for Mathematics Education*, *1*(4), 437–454.

Gao, S., Lu, Y., Ooi, C. H., Cai, Y., & Gunawan, P. (2023). Designing interactive augmented reality application for student's directed learning of continuous distillation process. *Computers & Chemical Engineering*, *169*, 108086.

Gargrish, S., Kaur, D. P., Mantri, A., Singh, G., & Sharma, B. (2021). Measuring effectiveness of augmented reality-based geometry learning assistant on memory retention abilities of the students in 3D geometry. *Computer Applications in Engineering Education*, *29*(6), 1811–1824.

Gittinger, M., & Wiesche, D. (2024). Systematic review of spatial abilities and virtual reality: The role of interaction. *Journal of Engineering Education*, *113*(4), 919–938.

Haleem, A., Javaid, M., Qadri, M. A., & Suman, R. (2022). Understanding the role of digital technologies in education: A review. *Sustainable Operations and Computers*, *3*, 275–285.

Hanid, M. F. A., Zakaria, M. I., & Hassan, R. (2025). The advancement of extended reality in education: Insights from a 2019–2024 bibliometric analysis. *Multimedia Tools and Applications*, 1–25.

Hasanah, N. R., Turmudi, T., Juandi, D., Herman, T., & Supatmi, S. (2024). 5E-STEM Model Integration: Enhancing Mathematical Reflective Thinking through 3D and Augmented Reality (AR). *2024 International Conference on Informatics Engineering, Science & Technology (INCITEST)*, 1–8.

Hasanah, N. R., Turmudi, T., Juandi, D., & Jupri, A. (2024). Investigation of TPACK Skills of Elementary to Secondary School Teachers in the Context of Educational Technology: Profile and Challenges. *Jurnal Penelitian Pendidikan IPA*, *10*(7), 3894–3904.

Hasanah, N. R., Turmudi, T., Juandi, D., & Roesdiana, L. (2025). Enhancing students reflective thinking through outdoor play and game-based contextual learning. *Retos: Nuevas Tendencias En Educación Física, Deporte y Recreación*, *62*, 304–309. https://doi.org/https://doi.org/10.47197/retos.v62.109379

Hasanah, N. R., Turmudi, T., Juandi, D., & Wahyudin, W. (2025). Development of 3D Visualization Media Using Assemblr Studio for Learning Polyhedral Geometry. *The Eurasia Proceedings of Educational and Social Sciences*, *45*, 66–74.

Hmoud, M., Swaity, H., Karram, O., Shibli, H., Swaity, S., & Daher, W. (2023). High school students' engagement in biology in the context of XR technology. *IEEE Access*, *11*, 137053–137066.

Huang, T.-C., & Tseng, H.-P. (2025). Extended Reality in Applied Sciences Education: A Systematic Review. *Applied Sciences*, *15*(7), 4038.

İbili, E., Çat, M., Resnyansky, D., Şahin, S., & Billinghurst, M. (2020). An assessment of geometry teaching supported with augmented reality teaching materials to enhance students' 3D geometry thinking skills. *International Journal of Mathematical Education in Science and Technology*, *51*(2), 224–246.

Iqbal, M. Z., & Campbell, A. G. (2023a). AGILEST approach: Using machine learning agents to facilitate kinesthetic learning in STEM education through real-time touchless hand interaction. *Telematics and Informatics Reports*, *9*, 100034.

Iqbal, M. Z., & Campbell, A. G. (2023b). Real-time hand interaction and self-directed machine learning agents in immersive learning environments. *Computers & Education: X Reality*, *3*, 100038.

Jablonski, S., & Ludwig, M. (2023). Teaching and learning of geometry—A literature review on current developments in theory and practice. *Education Sciences*, *13*(7), 682.

Jagatheesaperumal, S. K., Ahmad, K., Al-Fuqaha, A., & Qadir, J. (2024). Advancing education through extended reality and internet of everything enabled metaverses: applications, challenges, and open issues. *IEEE Transactions on Learning Technologies*, *17*, 1120–1139.

Jamah, A., Alnagrat, A., Ismail, R. C., Idrus, Z. S., Mansour, R., & Alfaqi, A. (2022). A Review of Extended Reality (XR) Technologies in the Future of Human Education: Current Trend and Future Opportunity. *1*, *2*, 81–96.

Kress, B. C., & Chatterjee, I. (2021). Waveguide combiners for mixed reality headsets: a nanophotonics design perspective. *10*, *1*, 41–74.

Lampropoulos, G., Keramopoulos, E., Diamantaras, K., & Evangelidis, G. (2022). Augmented reality and gamification in education: A systematic literature review of research, applications, and empirical studies. *Applied Sciences*, *12*(13), 6809.

Lindner, P., Miloff, A., Fagernäs, S., Andersen, J., Sigeman, M., Andersson, G., Furmark, T., & Carlbring, P. (2019). Therapist-led and self-led one-session virtual reality exposure therapy for public speaking anxiety with consumer hardware and software: A randomized controlled trial. *Journal of Anxiety Disorders*, *61*, 45–54.

Lowrie, T., & Logan, T. (2023). Spatial visualization supports students' math: mechanisms for spatial transfer. *Journal of Intelligence*, *11*(6), 127.

Meccawy, M. (2022). Creating an immersive XR learning experience: A roadmap for educators. *Electronics*, *11*(21), 3547.

Memarian, B., & Doleck, T. (2024). A novel ethical analysis of educational XR and AI in literature. *Computers & Education: X Reality*, *4*, 100052.

Mouali, S., Sefian, M. L., & Bakkali, I. (2024). Augmented and Virtual Reality for Mathematics Education: A Narrative Review. In *Technological Tools for Innovative Teaching* (pp. 179–198).

Ng, O.-L., Shi, L., & Ting, F. (2020). Exploring differences in primary students' geometry learning outcomes in two technology-enhanced environments: dynamic geometry and 3D printing. *International Journal of STEM Education*, *7*, 1–13.

Nikou, S. A., Perifanou, M., & Economides, A. A. (2024). Development and validation of the teachers' augmented reality competences (TARC) scale. *Journal of Computers in Education*, *11*(4), 1041–1060.

Oh, H., & Son, W. (2022). Cybersickness and its severity arising from virtual reality content: A comprehensive study. *Sensors*, *22*(4), 1314.

Park, S., & Lee, G. (2020). Full-immersion virtual reality: Adverse effects related to static balance. *Neuroscience Letters*, *733*, 134974.

Pérez-Juárez, M. Á., González-Ortega, D., & Aguiar-Pérez, J. M. (2023). Digital distractions from the point of view of higher education students. *Sustainability*, *15*(7), 6044.

Radianti, J., Majchrzak, T. A., Fromm, J., & Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. *Computers & Education*, *147*, 103778.

Rossano, V., Lanzilotti, R., Cazzolla, A., & Roselli, T. (2020). Augmented reality to support geometry learning. *IEEE Access*, *8*, 107772–107780.

Sarkar, P., Kadam, K., & Pillai, J. S. (2020). Learners' approaches, motivation and patterns of problem-solving on lines and angles in geometry using augmented reality. *Smart Learning Environments*, *7*, 1–23.

Schwaiger, M., Krajnčan, M., Vukovič, M., Jenko, M., & Doz, D. (2024). Educators' opinions about VR/AR/XR: An exploratory study. *Education and Information Technologies*, 1–20.

Shaghaghian, Z., Burte, H., Song, D., & Yan, W. (2022). An Augmented Reality Application and User Study for Understanding and Learning Spatial Transformation Matrices. *ArXiv*, 2212.00110.

Simonetti, M., Perri, D., Amato, N., & Gervasi, O. (2020). Teaching math with the help of virtual reality. *Computational Science and Its Applications – ICCSA 2020: 20th International Conference, Cagliari, Italy, July 1–4, 2020, Proceedings, Part VII*, 799–809.

Spilka, D., & SpilkaIs, D. (2023). Is virtual reality bad for our health? Studies point to physical and mental impacts of VR usage. *Springer Nature*.

Su, Y.-S., Cheng, H.-W., & Lai, C.-F. (2022). Study of virtual reality immersive technology enhanced mathematics geometry learning. *Frontiers in Psychology*, *13*, 760418.

Szymkowiak, A., Melović, B., Dabić, M., Jeganathan, K., & Kundi, G. S. (2021). Information technology and Gen Z: The role of teachers, the internet, and technology in the education of young people. *Technology in Society*, *65*, 101565.

Taborda, C. L., Nguyen, H., & Bourdot, P. (2025). Engagement and Attention in XR for Learning: Literature Review. *International Conference on Virtual Reality and Mixed Reality*, 207–242.

Tarng, W., Huang, J. K., & Ou, K. L. (2024). Improving Elementary Students' Geometric Understanding Through Augmented Reality and Its Performance Evaluation. In *Systems*. mdpi.com. https://www.mdpi.com/2079-8954/12/11/493

Thamrongrat, P., & Law, E. L.-C. (2019). Design and evaluation of an augmented reality app for learning geometric shapes in 3D. *IFIP Conference on Human-Computer Interaction*, 364–385.

Theodoropoulos, T., Makris, A., Boudi, A., Taleb, T., Herzog, U., Rosa, L., Cordeiro, L., Tserpes, K., Spatafora, E., & Romussi, A. (2022). Cloud-based XR services: A survey on relevant challenges and enabling technologies. *Journal of Networking and Network Applications*, *2*(1), 1–22.

Ventouris, A., Panourgia, C., & Hodge, S. (2021). Teachers' perceptions of the impact of technology on children and young people's emotions and behaviours. *International Journal of Educational Research Open*, *2*, 100081.

Walkington, C., Nathan, M. J., Washington, J., Hunnicutt, J., Darwin, T., Daughrity, L., & Schenck, K. (2024). Comparing learning geometry using a tablet to head-mounted display augmented reality: How and when dimensionality matters. *Education and Information Technologies*, 1–30.

Wang, Z., Wang, R., Wu, J., Zhang, W., & Li, C. (2024). Dynamic Resource Allocation for Real-Time Cloud XR Video Transmission: A Reinforcement Learning Approach. *IEEE Transactions on Cognitive Communications and Networking*, *10*(3), 996–1010.

Wong, J. Y., Azam, A. B., Cao, Q., Huang, L., Xie, Y., Winkler, I., & Cai, Y. (2024). Evaluations of virtual and augmented reality technology-enhanced learning for higher education. *Electronics*, *13*(8), 1549.

Yaniawati, P., Indrawan, R., & Mubarika, M. P. (2023). The Potential of Mobile Augmented Reality as a Didactic and Pedagogical Source in Learning Geometry 3D. *Journal of Technology and Science Education*, *13*(1), 4–22.

Zhang, Y., Feijoo-Garcia, M. A., Gu, Y., Popescu, V., Benes, B., & Magana, A. J. (2024). Virtual and augmented reality in Science, Technology, Engineering, and Mathematics (STEM) education: an Umbrella Review. *Information*, *15*(9), 515.

Zhou, Y., & Divekar, R. (2025). Immersive, Task-Based Language Learning Through XR and AI: From Design Thinking to Deployment. *TechTrends*, 1–20.