MathEdu Journal of the Korean Society of Mathematical Education Series A

Research Article

The Mathematical Education 2024;63(2):295-318
https://doi.org/10.7468/mathedu.2024.63.2.295
pISSN 1225-1380, eISSN 2287-9633

A narrative review on immersive virtual reality in enhancing high school students' mathematics competence: From TPACK perspective

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ABSTRACT

This narrative review explores the transformative potential of immersive virtual reality (IVR) in enhancing high school students' mathematics competence, viewed through the lens of the technological, pedagogical, and content knowledge (TPACK) framework. This review comprehensively illustrates how IVR technologies have not only fostered a deeper understanding and engagement with mathematical concepts but have also enhanced the practical application of these skills. Through the careful examination of seminal papers, this study carefully explores the integration of IVR in high school mathematics education. It highlights significant contributions of IVR in improving students' computational proficiency, problem-solving skills, and spatial visualization abilities. These enhancements are crucial for developing a robust mathematical understanding and aptitude, positioning students for success in an increasingly technology-driven educational landscape. This review emphasizes the pivotal role of teachers in facilitating IVR-based learning experiences. It points to the necessity for comprehensive teacher training and professional development to fully harness the educational potential of IVR technologies. Equipping educators with the right tools and knowledge is essential for maximizing the effectiveness of this innovative teaching approach. The findings also indicate that while IVR holds promising prospects for enriching mathematics education, more research is needed to elaborate on instructional integration approaches that effectively overcome existing barriers. This includes technological limitations, access issues, and the need for curriculum adjustments to accommodate new teaching methods. In conclusion, this review calls for continued exploration into the effective use of IVR in educational settings, aiming to inform future practices and contribute to the evolving landscape of educational technology. The potential of IVR to transform educational experiences offers a compelling avenue for research and application in the field of mathematics education.

Keywords Immersive virtual reality, TPACK framework, High school mathematics, Narrative review, and mathematics competence

Received March 4, 2024; **Revised** April 4, 2024; **Accepted** May 6, 2024

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2000 Mathematics Subject Classification 97C80

Introduction

Since the inception of the first virtual reality (VR) in the 1960s, pioneered by Ivan Sutherland and his student Bob Sproull, VR technologies have transcended their initial entertainment purpose (Hamad & Jia, 2022) to become a transformative media across various fields, such as education (Freina & Ott, 2015; Hu-Au & Lee, 2017; Kamińska et al., 2019), healthcare (Brickhead et al., 2019; Laver, 2020; Pottle, 2019), and entertainment (Jia & Chen, 2017; Rothe & Hußmann, 2018; Shafer et al., 2018). As noted by Di Natale et al. (2020), technological breakthroughs have enabled the creation of various VR simulations, which can be classified into three main categories (Table 1). Researchers categorized types of VR technologies based on their levels of immersion, which include (a) non-immersive, (b) sub-immersive, and (c) immersive technologies by researchers (Di Natale et al., 2020). Freina and Ott (2015) defined non-immersive VR as computer-based tools that simulate either real or imaginary environments. Desktop VR is an example of non-immersive VR (Di Natale et al., 2020; Furht, 2008). In contrast, immersive VR (IVR) provides users with a realistic experience by allowing them to feel psychologically present within a simulated environment (Bailey & Bailenson, 2017). Examples of immersive VR technologies involve cardboard, head-mounted display (HMD), and Cave Automated Virtual Environment (CAVE). Finally, semi-immersive VRs offer a partially virtual environment that is primarily utilized for educational and training applications, where users are engaged with graphical computing and large projector systems within this setting (Martirosov et al., 2022). Some examples of semi-immersive VR technologies include Full Dome, Embodied Mixed Reality Learning Environments (EMRELE), and smart glass (Di Natale et al., 2020). Table 1 outlines the three primary categories of virtual reality based on their level of immersion, along with their respective technology and definition. Considering this technological progress, VR's ability to immerse users within a digital learning environment has opened a new avenue for engagement and experiential learning (Park et al., 2023), particularly in educational settings. Among many VR applications, its integration into educational contexts stands out for its educational potential regarding how students learn and interact with complex subjects (Di Natale et al., 2020; Slater & Sanchez-Vivez, 2016), notably mathematics.

The advancement of IVR technologies also represents a pivotal advancement in the educational domain, especially in enhancing mathematics education. IVR, by simulating real-life environments and fully engaging the user's senses, transcends conventional teaching approaches, creating a deeply immersive learning experience. This heightened sense of presence and immersion, unique to IVR, particularly enables learners to experience and interact with mathematical concepts in ways previously unimaginable, thereby fostering a profound understanding and knowledge retention (Schnack et al., 2019). For example, the significance of IVR in education, particularly for its ability to deliver complex subjects such as mathematics through dimensional analysis, has been increasingly recognized, underscoring its potential to transform educational practices and outcomes (Radianti, 2020; Estapa & Nadolny, 2015). This review, therefore, seeks to explore the integration of IVR within high school mathematics education, emphasizing the balance between technological innovation and its educational impacts. By exploring how IVR can enhance dimensional analysis and foster mathematical competence, this review aims to highlight the transformative potential of IVR in enriching the educational landscape, particularly within the K-12 setting.

The ability to comprehend, apply, and manipulate mathematical concepts and skills is known as mathematics competence, and it goes beyond simple computational proficiency. It encompasses a deep comprehension of mathematical principles, problem-solving skills, and the capacity to apply mathematical knowledge in various contexts (Corrêa & Haslam, 2021). The integration of IVR in mathematics education offers a unique opportunity to foster these competencies, providing students with interactive and engaging experiences that conventional teaching approaches may not offer. This immersive technology creates a sense of presence akin to real-life experiences, thereby providing hands-on learning opportunities and the development of crucial skills in mathematics education (Schnack et al., 2019; Elme et al., 2022). Given the potential of IVR to enhance learning outcomes and student engagement, this review revisits existing research on IVR application in mathematics education. Specifically, through the lens of the Technological Pedagogical Content Knowledge (TPACK) framework, it aims to provide a comprehensive view of IVR's impacts and design mechanisms on students' mathematical competence, contributing to a deeper understanding of its educational implications.

Implementing immersive virtual reality (IVR) in K-12 education has gained popularity over the past decade (Di Natale et al., 2020; Pellas et al., 2021). One of the factors contributing to the popularity of IVR is its ability to engage students through interaction with a virtual reality system using natural sensorimotor responses (Slater & Sanchez-Vives, 2016). Due to its ability to evoke learning behaviors that facilitate learning in educational settings, teachers began using VR technology to facilitate game-based learning, field trips, observations, role play, and simulations (Pellas et al., 2021). Moreover, the use of IVR technologies in STEM education offers the advantage of engaging students when interacting with a digital environment with an elevated level of immersion (Holly et al., 2021). Through this immersive and highly interactive experience, students can be engaged in different cognitive, affective, and body mechanisms, contributing to dynamic, authentic, and meaningful learning experiences (Dalgarno & Lee, 2010).

Despite the advantages of IVR in teaching mathematics, teachers face technological challenges when trying to integrate IVR in math education due to its cost and complexity of use (Fransson et al., 2020). In order to address this issue, we propose using the TPACK as an instructional design framework to gain a deeper understanding of how math teachers can effectively integrate IVR in math education, especially at the secondary level (Fragkaki et al., 2022; Koehler & Mishra, 2009). TPACK focuses on technology integration in conjunction with content, pedagogy, and technology, which are all interrelated elements. By definition, TPACK refers to the successful integration of technology into teaching, which requires creating, maintaining, and re-establishing a dynamic balance among all components (Koehler & Mishara, 2009) In this review, we will explore how teachers develop an understanding of using IVR technologies to represent mathematical concepts. Additionally, we will discuss how teachers can use these technologies in a constructive manner to present math learning content and address some of the challenges faced by students.

Application of TPACK Framework to Immersive Virtual Reality in High School Mathematics Education

TPACK is a grounded theoretical framework that can interpret teachers' competencies engaging learning opportunities in the classroom (Marougkas et al., 2023). As illustrated in Figure 1, the TPACK model incorporates technology into classroom instruction by harmonizing three essential components: content knowledge (CK), pedagogical knowledge (PK), and technological knowledge (Mishra & Koehler, 2006). The first component, CK, represents a teacher's depth of understanding of the content they are teaching (Loewenberg Ball et al., 2008). PK refers to the strategies, procedures, and methods used by teachers to deliver curriculum content effectively, while considering students' diverse learning needs (Kanuka, 2006; Sahin, 2011). Finally, TK encompasses the abilities and expertise required to utilize specific technologies, including IVR technologies (Koehler & Mishra, 2006). It is important to note that these three components are interconnected and interdependent, rather than distinct areas of knowledge.

These three fundamental components (i.e., content, pedagogical, and technological) can lead to four distinct intersection categories, namely Pedagogical Content Knowledge (PCK), Technological Content

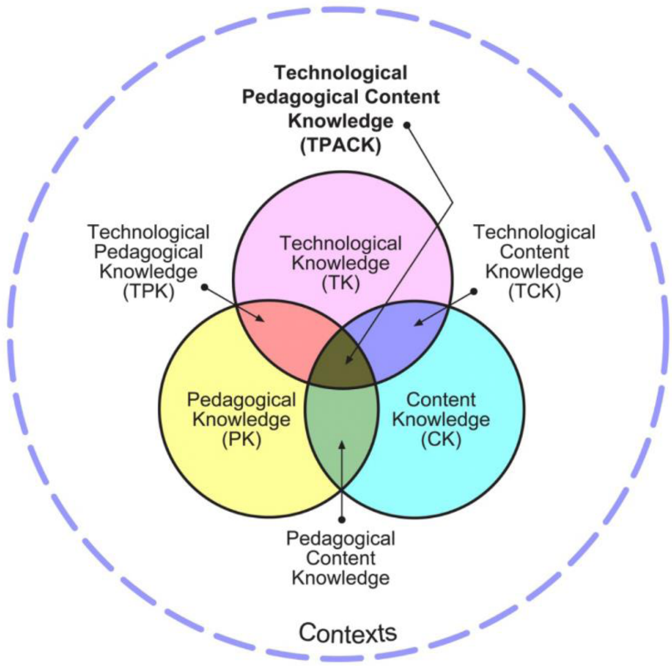

Figure 1. TPACK Framework by Mishra and Koehler (2006).

Knowledge (TCK), Technological Pedagogical Knowledge (TPK), and TPACK (Mishra & Koehler, 2006). PCK represents the strategies that enable teachers to effectively present and articulate a subject or concept in a way that enhances student comprehension (Shulman, 1986). TCK pertains to how teachers use technology to provide students with better perspectives on the subject matter (Koehler & Mishra, 2006). TPK describes the teachers' awareness of appropriate technology tools to support teaching and learning processes. Understanding the interconnection of these knowledge types is essential for effective technology integration in the classroom, requiring a deep understanding of pedagogical implications and mastery of the content being taught. Therefore, TPACK emphasizes a nuanced and comprehensive approach to incorporating technology into education, considering the complex relationship between technology, pedagogy, and content (Koehler & Mishra, 2006).

The application of TPACK in secondary mathematics education presents an opportunity for teachers to enhance their understanding of the effective deployment of IVR for representing mathematical concepts. TPACK necessitates teachers to possess competencies across the interconnected relationships between pedagogy, content, and technology to deliver impactful instruction in secondary mathematics with IVR. Incorporating TPACK into this literature synthesis offers teachers better strategies for integrating IVR into math classes, thereby improving their instructional skills and providing students with a more engaging and interactive learning experience.

Through a close examination of empirical studies in the application of IVR in mathematics education, this review seeks to highlight practical implementations and outcomes of IVR in mathematics education, underpinned by TPACK. These studies serve as a testament to the transformative power of integrating IVR within a structured pedagogical framework, addressing both the opportunities and challenges it presents. It allows for an assessment of how educators can integrate such technologies into their instructional practices, mindful of the specific challenges posed by the mathematical content. This literature synthesis, taking a holistic approach, ensures that the integration of IVR transcends technological novelty, becoming a pivotal element in crafting deeply engaging and pedagogically sound educational experiences that resonate with the diverse needs of learners.

Background of the Study

1. Benefits and Limitations of Facilitating Immersive Virtual Reality in Mathematics Education

High school students are preparing to enter a world where digital literacy and technological proficiency are critical (Baterna et al., 2020). Integrating IVR into their education not only enhances their current learning experiences (Papanastasiou et al., 2019) but also prepares them for future academic and professional environments where virtual and augmented realities will play a significant role (Vakaliuk et al., 2020). By familiarizing high school students with IVR technologies, educators are helping them develop the skills and confidence to navigate future technological landscapes (Papanastasiou et al., 2019) inherent to STEM education.

IVR technologies, particularly when integrated into high school mathematics education, offer distinct advantages that align closely with their developmental milestones and educational needs (Su et al., 2022). Educators can help address individual learning needs and preferences by engaging students in immersive experiences facilitated by IVR (Calvert & Hume, 2022; Ceja-Salgado & Price, 2019). This personalized approach enhances comprehension of mathematical concepts and ensures that IVR is utilized meaningfully to augment the overall learning process (Elme et al., 2022). In this way, the teacher's role becomes multifaceted, encompassing IVR technology's facilitation and instruction tailored to meet each student's unique learning needs. Through immersive experiences provided by IVR, educators can create a personalized learning environment that fosters a deeper understanding of mathematical concepts (Di Natale et al., 2020). This multifaceted role involves guiding students in using IVR technology and adapting teaching strategies to align with individual preferences, enhancing the overall educational experience (Elme et al., 2022).

Teachers play a pivotal role in successfully integrating IVR into mathematics education, significantly enhancing students' learning experiences (Fransson et al., 2019). However, integrating virtual reality technology in K-12 schools may present specific requirements and difficulties for teachers (Araiza-Alba, 2022; Fransson et al., 2020; Gokumas & Izzouzi, 2023). The initial investment in VR equipment and software poses a financial barrier, particularly for schools with limited resources. Based on Fransson et al.'s (2020) empirical study, the teachers reported significant challenges in using a head-mounted display (HMD)-supported VR in education. Those challenges include (1) economic and technological challenges, (2) initial learning barriers, such as dealing with the functionality of the device, (3) organization and practical enactment for teaching and learning, (4) curricula, syllabuses, and expected learning outcomes, and (5) teachers' 'competences, professional development, and trust. Many teachers have stated that the cost of the entire HMD-supported VR equipment and its software can be costly and too complicated to use. Thus, financial constraints may create disparities in educational opportunities, as not all schools can afford to embrace IVR technology. This challenge is linked to the identified themes and trends in literature, where the unequal distribution of resources impedes the exploration of IVR effectiveness. The excessive costs associated with IVR can inhibit widespread adoption, limiting the ability of educational institutions to harness its potential benefits (Romano et al., 2023). Thus, school administrators need to support teachers' skills and knowledge of implementing IVR by providing comprehensive hands-on training for educators, allowing them to become familiar with the intricacies of IVR technology and its diverse applications (Sami et al., 2023). This training equips teachers with the skills and confidence to incorporate IVR tools into their teaching methods effectively. Furthermore, ongoing professional development is crucial to ensure that teachers stay abreast of the latest advancements in IVR and can seamlessly integrate them into their evolving educational practices (Lee et al., 2021). This continuous learning approach empowers educators to adapt and optimize IVR resources to suit the dynamic needs of their students and curriculum.

While increasing evidence supports the effectiveness of IVR in education, existing literature on its application within mathematics education remains limited and inadequately synthesized (Hamilton et al., 2021). A notable study emphasized the necessity for further research investigating the specific design and implementation of VR in mathematics education, especially in online environments (Chan et al., 2020). Using the TPACK framework, this review evaluates IVR's application in high school mathematics, emphasizing the synergy between technological innovation, pedagogical strategies, and content mastery. By dissecting successful implementations of IVR, we identify key factors that contribute to effective learning environments, highlighting how educators can harness IVR to enrich students' understanding of mathematics. The primary focus is exploring IVR's intricate design and seamless integration to enhance mathematical competence. The review also aims to present a detailed account of the current state of IVR in mathematics education, highlighting relevant studies that thoroughly examined its effectiveness.

2. Rationale for the Review

Previous studies have noted the significance of IVR (Di Natale et al., 2020; Pellas et al., 2021; Su et al., 2022) which provided insights into the potential of IVR in fostering student engagement and improving comprehension of mathematical concepts. However, despite the recognized potential of IVR on such outcomes, a literature synthesis on the role of IVR in enhancing mathematics competence appears limited. This review aims to fill this gap by highlighting IVR's unique benefits and applications in mathematics education. Unlike conventional virtual reality (VR) that involves desktop settings, IVR engages students in realistic and highly interactive simulation-based learning situated in mathematics, offering a novel and potentially more effective learning approach. IVR's capacity to visualize abstract mathematical concepts in three-dimensional spaces can deepen understanding and spatial visualization skills (Nathal et al., 2018). Furthermore, the present study aims to discover the potential of IVR because it provides a unique and heightened sense of presence and engagement that is distinct from non-immersive experiences (Calvert et al., 2022; Di Natale et al., 2020). This heightened immersion has been shown in assorted studies reporting its impact on learning outcomes and student engagement. While non-immersive VR approaches have been prevalent in wide educational settings due to practical constraints, such as cost and equipment availability, our goal is to explore the full potential of IVR.

The primary objective of this narrative review is twofold: (a) to explore the design principles and integration strategies of IVR in mathematics education and (b) to review its contribution to students' mathematics competence. Also, this narrative review aims to summarize the current state of IVR in the field and critically analyze relevant studies. By providing a comprehensive overview of the field, this paper aims to inform educators, researchers, and policymakers about IVR's potential advantages and suggest future research and educational practices.

3. Research Questions

Specifically, the study will seek to answer the following questions:

- RQ1: How does IVR technology enhance high school students' mathematics competence?
- RQ2: What pedagogical strategies did teachers utilize in implementing IVR in high school mathematics education?
- RQ3: What are the pedagogical factors that need to be considered when creating math lessons using IVR?

Methods

The study employed a narrative review methodology to synthesize the existing literature on immersive virtual reality in enhancing high school students' mathematics competence, using the TPACK framework as a guiding lens. A narrative review is a type of literature review that aims to provide a comprehensive and subjective summary of the existing literature on a particular topic (Barker et al., 2024). Therefore, the narrative review is suitable for our study due to its ability to synthesize diverse research related to IVR in mathematics education comprehensively.

1. Search Strategy

The article selection process was structured into three main phases: identification, screening, and inclusion (Page et al., 2021). The researchers of this study reviewed IVR in high school mathematics education literature through searching the following databases: ERIC, EBSCOhost, ScienceDirect, Web of Science, ERIC, and APA PsycINFO. Due to the scarcity of the literature, the researchers employed a snowballing technique (Booth et al., 2016) to locate supplementary articles, until no further relevant studies were found.

Guided by the PICO framework (i.e., Population, Intervention, Comparison/Context, and Outcome; Booth et al., 2016), the researchers used specific search strings to look for articles, as shown in Table 1. During the retrieval of articles from academic databases and search engines, the authors used a combination of search terms, wildcards, and Boolean operators. For the population, the search terms were "High school student* OR secondary student*" AND virtual reality in education. While the intervention includes "Virtual reality in education OR IVR, or immersive VR." The context includes "High school or secondary school or ninth grade or tenth grade or eleventh grade or twelfth grade AND mathematics or math or math education or mathematics education." Finally, the search terms for outcome are "Math competenc*."

Table 1. List of search terms based on PICO framework

PICO Elements	Search Terms
Population	High school student* OR secondary student* AND virtual reality in education
Intervention	Virtual reality in education OR IVR or immersive VR
Context	High school or secondary school or ninth grade or tenth grade or eleventh grade or twelfth grade AND mathematics or math or math education or mathematics education
Outcome	Math competenc*

2. Inclusion and Exclusion Criteria

This narrative review included articles published in English from January 2010 and February 2024. Both peer-reviewed articles and grey literature (e.g., conference proceedings, theses, and dissertations) were eligible if they focused on the application of IVR in high school mathematics education. We excluded articles not in English or published before January 2010, as well as for studies that were systematic or scoping reviews, and meta-analyses. The literature search for this study was initiated from the year 2010 onwards in light of the substantial advancements observed in educational VR technology, particularly with the introduction of innovative devices post-2009, as highlighted by Pellas et al. (2020). By focusing our search on articles published after 2010, we aimed to ensure that our review encompassed the most current and relevant research in the field.

The initial database search yielded 351 articles, and the screening process commenced with removing

Table 2. Comparison of virtual reality technologies based on the degrees of immersion (Di Natale et al., 2020)

Degrees of immersion	Virtual reality technology	Definition
Non-immersive	Desktop virtual reality	Desktop VR enables users to computer monitor for virtual reality applications (Furht, 2008)
Semi-immersive	Fulldome	Full-dome, derived from the planetarium concept, immerses users within a large dome-centered projection environment and is accompanied by surround sound (Schnall et al., 2012).
	Embodied Mixed Reality Learning Environments (EMRELE)	The Situated Multimedia Arts Learning Lab (Johnson-Glenberg, Birchfield, & Usyal, 2009) serves as an example of EMRELE. It utilizes motion capture technology and a highly collaborative pedagogy to engage the sensory systems, such as visual and auditory, that humans rely on for learning (Johnson-Glenberg et al., 2014).
	Smart glass	Smart Glass is based on the Optical Head-mounted Display (OHMD) technology, enabling users to wear the device while receiving information through an external glass that effectively delivers the specific information sought by the users (Kim & Choi, 2021).
Immersive	Cardboard	"Cardboard VR is a do-it-yourself kit that utilizes a piece of cardboard with a magnet, a rubber band and a couple of pieces of plastic lenses" (Amin et al., 2016, p.271)
	Head-mounted display (HMD)	Head-mounted displays (HMDs) offer immersive representations of virtual environments utilizing 3D models, spherical videos, and virtual field trips (Wu et al., 2020). Moreover, they elevate the educational experience and enhance manipulation abilities during simulations.
	Cave Automated Virtual Environment (CAVE)	The CAVE system is a room-based fully IVR technology that has the capability to project scenes onto the ceiling, resulting in a six-wall or six-sided CAVE experience (Muhanna, 2015).

duplicate articles, which left 297 articles. The authors then scrutinized titles and abstracts to eliminate those unrelated to the study goals. This process led to 14 publications qualified for full-text review. After the full-text screening, the authors finally identified a total of 11 articles that met all criteria for relevance to the research, concluding the detailed screening process. Table 2 presents the complete list of the articles that involved the VR hardware and software developed for a virtual world. The population criteria encompass high school or secondary school students, ranging from 12 to 19 years old. Moreover, we have specified the grade level as grades 9 through 12, offering additional clarity regarding the targeted participants. This distinction is important as secondary education may encompass middle school students in certain countries.

3. Data Analysis

We used thematic analysis in examining our study dataset. This method allowed us to identify both overarching patterns and recurring themes within the data, each pertinent to our investigation (Braun & Clarke, 2006). In accordance with the principles of thematic analysis, our approach began with a process of data familiarization, code generation, pattern formation, and theme identification. Subsequently, we defined and labeled these themes before finalizing our report. Table 3 show the result of the initial search of the databases.

Table 3. Result of the initial search of the databases

Databases and Search Engine	Keywords	Frequency (N)
ERIC	(high school or secondary school or ninth grade or tenth grade or eleventh grade or twelfth grade) AND (virtual reality in education) AND (mathematics or math or math education or mathematics education) OR (IVR or immersive VR)	34
ScienceDirect	(high school) AND (mathematics or math or math education or mathematics education (AND (IVR)	88
Web of Science	(high school or secondary school or ninth grade or tenth grade or eleventh grade or twelfth grade AND virtual reality in education) AND (mathematics or math or math education or mathematics education) OR (IVR or immersive VR)	213
APA PsychInfo	(high school or secondary school or ninth grade or tenth grade or eleventh grade or twelfth grade AND (virtual reality in education) AND mathematics or math or math education or mathematics education) OR (Virtual reality in education OR IVR or immersive VR)	7
Google Scholar	(mathematics or math or "math education" or "mathematics education") AND ("virtual reality" or VR or" augmented reality" or immersive) AND ("high school" or "secondary school") AND ("online learning" or "e-learning or distance learning")	9
Total		351

Findings

1. RQ1: How Does Immersive Virtual Reality Technology Enhance High School Students' Mathematics Competence?

Based on the comprehensive review conducted on IVR in enhancing high school students' mathematics competence from the TPACK perspective, specifically, technological (T), pedagogical (P), and content (C) knowledge, the following key findings have emerged (Table 4):

Table 4. Key themes aligned with RQ1

Key themes	References
Effectiveness in teaching systems of equations	(Hsu, 2021)
Enhancement of engagement and motivation	(Perri et al., 2021; Su et al., 2022)
Facilitation of spatial visualization skills	(Gwee, 2013)
Teaching abstract mathematical concepts	(Gwee, 2013; Hsu, 2020; Perri et al., 2021; Shi et al., 2022; Su et al., 2022)

(1) Effectiveness in Teaching Systems of Equations

IVR technology has demonstrated its effectiveness in teaching complex mathematical concepts, such as systems of linear equations in multiple variables. Studies have shown that when combined with traditional curriculum, IVR facilitates effective learning, particularly when using desktop-based VR systems. Studies such as the one by Hsu (2021) demonstrate the effectiveness of IVR technology in teaching complex mathematical concepts like systems of linear equations in several variables. This study tested two auxiliary teaching systems, including desktop-based VR. This effectiveness could be attributed to the immersive nature of VR, which allows students to visualize abstract concepts in a more tangible way, leading to better understanding and retention. Furthermore, the study found that desktop-based VR systems were superior in enhancing performance due to their high-efficiency display and better control, as indicated by the research.

(2) Enhancement of Engagement and Motivation

The use of IVR techniques significantly increases students' understanding of abstract mathematics concepts. The systems guided students to be aware of mathematical functions useful, instructive, and motivating through learning experience design. Students using VR immersive learning systems demonstrate enhanced learning outcomes compared to traditional teaching methods. Perri et al. (2021) and Su et al. (2022) both provide evidence of how IVR techniques enhance students' engagement and motivation in mathematics education. Perri's study collected feedback from high school students who used AR and VR environments for mathematics learning, finding how playful learning environments stimulated students' interest and willingness to engage with mathematics. Similarly, Su et al. (2022)'s work showed that students using IVR systems demonstrated how to enhance better learning outcomes and motivation compared to conventional teaching methods. The immersive and interactive nature of IVR experiences appears to captivate students' attention and make the learning process more enjoyable and motivating, thereby enhancing their engagement and motivation.

(3) Facilitation of Spatial Visualization Skills

IVR, particularly when integrated with 3D animations, facilitates the development of spatial visualization skills among high school students, contributing to an improved understanding of geometric concepts. Gwee (2013) conducted a study that explored the effects of IVR supported programs on the spatial visualization skills of secondary school students. The study found that students using the IVR-supported program improved in spatial visualization skills compared to those taught using conventional methods such as whiteboards or paper. This suggests that the immersive and interactive nature of IVR—coupled with its ability to provide dynamic visualizations—offers a unique advantage in enhancing spatial cognition and geometric understanding among students. A speculation from this study is that IVR's naturalistic user interaction features helped students to activate hands-on exploration and manipulation of geometric figures in a semi-open-ended virtual space.

(4) Teaching Abstract Mathematical Concepts

Among the 11 articles examined, five empirical studies emphasized the importance of using IVR to teach complex mathematical concepts, such as geometry, linear equations (Gwee, 2013; Hsu, 2020; Perri et al., 2021; Shi et al., 2022; Su et al., 2022). Researchers (Hsu, 2020; Shi et al., 2022; Su et al., 2022) have discovered that IVR can improve learning motivation and learning effectiveness in the digital teaching of mathematics. Hsu (2020) conducted a quasi-experimental study and found that when integrating IVR in math education, it is important to consider the design of teaching materials. IVR has been found to be useful in presenting abstract learning concepts in a real-life context. Similarly, through an experimental approach, Su et al. (2022) found that high school students showed increased learning motivation in geometry through IVR. The experimental group noted that utilizing the IVR headset and 3D helmet made the learning process more enjoyable and enhanced their focus. The use of IVR technology and its materials sparked curiosity and enthusiasm in the students' learning experience. Therefore, teachers are advised to strategically incorporate IVR technology into high school mathematics instruction. For example, utilizing IVR through gamification can help address teaching challenges and engage students in the learning process (Shi et al., 2022). This shows that IVR can be a promising tool in enhancing understanding of abstract math concepts and improving overall student achievement (Hsu, 2020).

In line with this, some of the included studies have also revealed that when students are engaged in a virtual learning environment, it assists them in having hands-on learning experience and construct knowledge from virtual elements (Gwee, 2013; Perri et al., 2021). Gwee (2013) and Perri et al. (2021) argued that involving students in IVR-supported learning environments can help improve students' spatial knowledge and peripheral awareness, which are critical skills in geometry and any tasks requiring the visualization of shapes and patterns. According to Qiu et al. (2020), spatial knowledge encompasses environmental features, positional relationships between objects, and attributes of spatial connections. Therefore, exposing students to immersive virtual worlds increases brain stimulation during the learning phase, allowing them to better comprehend concepts through 3D objects, learn by doing, and construct knowledge from virtual elements (Gwee, 2013; Perri et al., 2021).

2. RQ 2: What Pedagogical Strategies Did Teachers Utilize in Implementing Immersive Virtual Reality in High School Mathematics Education?

Our analysis aimed to uncover underlying themes (Table 5) associated with the pedagogical knowledge (P) and content knowledge (c) components of the TPACK framework, particularly illustrating teachers' strategies to effectively integrate IVR technology into high school mathematics instruction.

Table 5. Key themes aligned with RQ2

Key themes	References
Incorporating game-based scenarios	(Christopoulos et al., 2024; Hsu, 2020; Lai et al., 2016; Perri et al., 2021; Shi et al., 2022; Su et al., 2022)
Equipping IVR learning environment with feedback mechanisms and problem-solving activities	(Chen, 2012; Hsu, 2020; Naranjo et al., 2020)
Using tangible interfaces and virtual worlds	(Guerrero et al., 2016; Hsu, 2021)

(1) Incorporating Game-based Scenarios

Among a total of 11 articles, six studies showed that immersive VR could be used by teachers in creating game-based scenarios (Christopoulos et al., 2024; Hsu, 2020; Lai et al., 2016; Perri et al., 2021; Shi et al., 2022; Su et al., 2022). Two of these articles explored how the virtual reality learning environment can be used in teaching mathematics concepts (Shi et al., 2022; Su et al., 2022). First, Shi et al. (2022) conducted a pretest and posttest experimental design to understand how teachers can use game-based scenarios to solve difficult teaching problems. The researchers and game designers developed a game based IVR learning environment to teach quadratic equations. Based on the findings, there were significant improvements in math achievement and learning motivation between the pretest and posttest among students who played the game. The improvement in learning and motivation was due to the integration of game components and their effectiveness in solving actual teaching problems. There was a balanced content-gameplay integration. Shi et al. (2022) also claimed that high school participants learned through the given situations in the game and by interacting with other learners and computerized learners. Finally, the game design has feedback mechanics that will automatically trigger the "help procedure" feature if the players commit three consecutive failures. Similarly, Su et al. (2022) used VR technology to develop a virtual reality immersive learning mathematics geometry system to enhance students' sensory experiences of mathematical geometry concepts. Most of the student participants in the experimental group reported that the use of immersive VR in learning mathematics and geometry systems enabled them to make the learning process fun, and it was easier to focus on their learning. Su et al. (2023) also discovered that the mode of completing the game can effectively give students a sense of accomplishment. Furthermore, having an additional instruction or manual for using immersive VR has contributed to the experimental group's perceived usefulness in using VR technology for learning geometry.

Perri et al. (2021) supported the abovementioned studies, where they claimed that the VR and Augmented reality (AR) techniques have significantly improved the students' level of understanding in mathematics through Unity3D, which allows the composition of the virtual environments. Unity3D was used to generate geometric figures that reduced their complexity in terms of the vertices. As one of the study's initial findings, most students found the introduction to the play environment using VR and AR useful and instructive. These simulations of 3D stimuli allow students to test their experiments in mathematical modeling with responsive 3D simulations (Alhammouri & DiNapoli, 2023). The creation of a virtual reality environment has enabled students to immerse themselves in virtual worlds that enhance cognitive stimulation during the learning phase. Moreover, Hsu's (2020) quasi-experimental design showed that VR can improve learning motivation and effectiveness in high school mathematics, especially through the accompaniment of VR tutorial materials.

In contrast, Christopoulos et al. (2023) engaged their student participants with the desktop-based 3D virtual learning environment to verify how immersion is associated with mathematical skill improvement. The research team designed and developed minigames that are appropriate for the students' ages and mathematical skills to help to increase immersion. The game mechanics of the game include realism, feedback, fun, challenges, Pavlovian interactions, assessment, and quick feedback. The changes in students' mathematical test scores were compared using paired sample t-tests. Unfortunately, there were no significant associations with the test results (Christopoulos et al., 2023).

(2) Equipping IVR Learning Environment with Feedback Mechanisms and Problem-Solving Activities

Three articles have also shown that the integration of practical content, performance assessment, and problem-solving activities can enhance mathematics learning using IVR (Chen, 2012; Hsu, 2020; Naranjo et al., 2020). Hsu (2020) states that integrating interactive game design in solving math operations and challenges. This is due to the interactive animation that caused the enthusiasm of the students to become challenged. Also, Hsu (2020) observed that the visuals in the VR game influence the students' understanding of the abstract concept in mathematics. Naranjo et al. (2020) discovered that VR design contributes to students' understanding of mathematics. In their initial study, virtual learning environments were developed to help students improve their knowledge by (1) adding menus where students can adjust the level of difficulty, (2) applying challenges that align with real-life scenarios, and (3) having a VR environment with a higher degree of complexity (Naranjo et al., 2020). Their initial findings showed that VR could contribute to improving the student's performance.

(3) Using Tangible Interfaces and Virtual Worlds

Two studies have also shown that the use of tangible interfaces (i.e., controlling virtual objects through the manipulation of physical objects) has assisted students in gaining more meaningful and durable learning concepts (Guerrero et al., 2016; Hsu, 2021). One of these studies was conducted by Hsu (2021), where an experimental research design was implemented to compare the impact of a desktop-based VR system (HTC VIVE) for VR auxiliary teaching, while the other used an all-in-one VR system (HTC VIVE Focus). Here, for terminology clarification, the HTC VIVE is categorized as a desktop-based VR system because it requires a wired connection to a desktop computer for operation. This contrasts with standalone or all-in-one VR systems, namely, the HTC VIVE Focus, which do not require an external computer as they have built-in processing capabilities. The researchers found that a desktop-based VR system (HTC VIVE) has been superior to an all-in-one VR system in learning effectiveness. This superiority was attributed to factors, such as the high-resolution display screen, six-degree-of-freedom handles, and connection to a high-end PC, which allowed for seamless handling of complex simulations. Furthermore, customized content development and effective integration of educational principles aided the desktop-based VR system's efficacy. The study emphasizes the importance of using technology and pedagogy together to improve learning outcomes in virtual reality environments.

Guerrero et al. (2016) also argued that having "virtual touch" technologies can help students learn geometry better than the traditional approach. Virtual touch technology facilitated active learning among students by enabling them to independently work through activities. In this context, teachers' primary responsibility was to provide initial guidance. This approach not only promotes student autonomy, but it also improves engagement and comprehension of geometric concepts through hands-on exploration and manipulation in a virtual environment.

3. RQ3: What Are the Pedagogical Factors that Need to be Considered When Creating Math Lessons Using Immersive Virtual Reality?

We also revisited pedagogical factors within the TPACK framework that are critical in the design and implementation of math lessons with IVR technology (Table 6).

Table 6. Key themes extracted aligned with RQ3

Key themes	References
Teacher pedagogical factor	(Naranjo et al., 2020; Perri et al., 2021)
Correlation with personality factors and curriculum	(Shi et al., 2022)
Strategic design of the IVR learning environment	(Lai et al., 2016; Guerrero et al., 2016; Hsu, 2020; Naranjo et al., 2020; Hsu, 2021; Shi et al., 2022)
Challenges and considerations	(Chen, 2012; Guerrero et al., 2016; Lai et al., 2016; Naranjo et al., 2020; Perri et al., 2021; Shi et al., 2021; 2022; Christopoulos et al., 2024).

(1) Teacher Pedagogical Factor

Pedagogical factors play a crucial role in shaping the effectiveness of IVR implementation in mathematics education. Research has shown various pedagogical strategies aimed at enhancing student engagement, motivation, and learning outcomes in this context. Naranjo et al. (2020) and Perri et al. (2021) have elucidated several such strategies. Naranjo et al. (2020) proposed a VR system based on the Singapore method, prioritizing problem-solving and logical reasoning over rote memorization. This approach empowers students to develop their problem-solving skills by applying fundamental concepts and heuristics in algebraic tasks. Similarly, Perri et al. (2021) utilized both AR and VR environments in high school mathematics classrooms and observed how the incorporation of XR-supported playful learning environments bolstered student engagement. These studies underscore the adaptability of 3D-represented interactions across diverse pedagogical approaches. For instance, interactive 3D simulations enable students to explore historical events virtually, immersing themselves in historical settings, and interacting with characters and artifacts, thereby fostering deeper engagement, motivation, and improved learning outcomes.

(2) Correlation with Personality Factors and Curriculum

As to pedagogical factors when using IVR, it is crucial to consider students' diverse profiles, including learning preferences, age groups, grade levels of students, as well as alignment with curriculum goals. Shi et al. (2022) assessed various personality factors using the Ten-Item Personality Inventory in China (TIPI-C), which evaluates five dimensions as follows: openness, neuroticism, extraversion, agreeableness, and conscientiousness. Extraversion encompasses traits such as sociability, assertiveness, and enthusiasm. The study findings revealed a significant correlation between extraversion and achievement improvement in GIVRLE, suggesting the potential suitability of certain GIVRLE designs for extroverted students. The correlation between extraversion and achievement improvement in the GIVRLE suggests that certain IVR design features could be more effective for extroverted students.

(3) Strategic Design of the IVR Learning Environment

The strategic design of IVR learning environments for mathematics education is pivotal, drawing upon several pedagogical factors that encompass game design, virtual environment design, interactive elements, and student engagement (Lim et al., 2006). First, the effectiveness of game based IVR environments on learning outcomes appears evident. Shi et al. (2022) emphasized the importance of game tasks, learning content integration, and visually enriched user experiences in enhancing student engagement and satisfaction. This highlights the significance of designing immersive VR experiences that gamify math lessons and integrate complex mathematical concepts seamlessly into gameplay. Second, the design of virtual environments plays a pivotal role in facilitating mathematical understanding. Studies by Hsu (2021) and Naranjo et al. (2020) demonstrate how interactive animations and diverse virtual environments can stimulate students' interest and engagement, thereby promoting deeper learning experiences. For instance, Hsu (2021) describes how geometrically dislocated interactive animation sparked enthusiasm among students and enhanced their understanding of complex mathematical concepts. Third, the integration of tangible user interfaces (TUIs) with virtual worlds offers opportunities for active learning and improved student outcomes. Guerrero et al. (2016) highlight how TUIs promote student autonomy, patience, and relaxation during learning activities, enhancing learning experiences in VR environments. Last, iterative design processes are crucial for optimizing VR math lessons. Lai et al. (2016) illustrate the importance of iterative modifications in-game software design to enhance user experience and learning outcomes. These modifications include adjustments to scoring mechanisms, the design of informative cues, and the selection of fitting virtual environments.

(4) Challenges and Considerations

Incorporating IVR into mathematics education holds significant promise for enhancing student engagement and learning outcomes. However, several challenges exist across different dimensions, as viewed through the TPACK framework. First, the accessibility and device equity are major concerns associated with IVR implementation in classroom. Disparities in access to IVR equipment and resources among schools and students across different socioeconomic backgrounds may exacerbate existing educational inequalities (Lai et al., 2016), echoing the importance of affordable IVR device options. Specifically, when it comes to affordance, there is a discrepancy between technology capabilities (i.e., user input and output) and student modality. IVR environments is designed to offer physically engaging experiences by stimulating various learning modalities. It deliberately enables students to experience the visual, auditory, and sometimes haptic senses, indicating multimodal cues. However, they also raise questions about the uniformity of learning experiences across different modalities. It naturally goes to the question of whether all students can equally benefit from IVR experiences. In other words, differences in sensory processing, motion sickness susceptibility, and even personal preferences for learning modalities are indicative that IVR is not likely to be the most effective learning tool for every student.

Second, technical limitations are another impediment to IVR's widespread adoption in mathematics education. The compatibility issues with existing educational technology infrastructure, can impede its implementation in classrooms (Perri et al., 2021). Furthermore, concerns about motion sickness, discomfort, and other negative effects experienced by users, particularly during IVR sessions, must be addressed in order to ensure a positive and safe learning environment (Hsu, 2020).

Third, teacher readiness and professional development are critical factors in the successful implementation of IVR in mathematics instruction (Naranjo et al., 2020). Educators require adequate training and learning support to effectively integrate IVR technology into their teaching practices, develop appropriate instructional strategies, and align IVR experiences with curriculum standards and learning objectives (Chen, 2012). Without adequate preparation and ongoing support, teachers may struggle to effectively use IVR to facilitate

Table 7. Articles identified by academic databases and search engines

Authors	Year	Title	VR hardware and software used	Math learning content	Math students' competencies that were observed/measured
Chen	2012	Development and evaluation of senior high school courses on emerging technology: a case study of a course on virtual reality	Shutter glasses or head-mounted displays (HMDs)	Coordinate systems, plane coordinate conversion, vectors, matrix, and curves in mathematics courses	Cognition of the importance of technology, performance of technology-related action, and technology career planning
Christopoulos et al.	2024	Is immersion in 3D virtual games associated with mathematical ability improvement in game-based learning?	Desktop-based 3D Virtual Learning Environment	1) Multiplication 2) Fractions line up 3) Quadratic function 4) Linear function 5) Radians conversion 6) Degrees conversion 7) Polygon 8) Cartesian 9) The scale factor 10) Up—liquid measurement	The improvements in functions, geometry, and thinking skills and methods
Guerrero et al.	2016	Integrating virtual worlds with tangible user interfaces for teaching mathematics: A pilot study	1) The first "tangible interface" device is FlyStick, which allows the user to control a virtual object in six degrees of freedom 2) The second "tangible interface" device is PrimBox which allows the user to modify virtual objects, changing attributes such as their position, size, rotation, and color	Geometry	Spatial perception and technical language of math and geometry
Gwee	2013	Effects of virtual-reality elements on spatial visualization skills of secondary three students in Singapore	A stereographic display subsystem and an interactive subsystem. The interactive subsystem has (1) a control pad to input commands and numbers; and (2) an input pen to create, edit, and manipulate 3D objects	Geometry	Spatial visualization skills, achievement in geometry, and attitude and behavior toward geometry
Hsu	2021	Exploring the effectiveness of two types of virtual reality headsets for teaching high school mathematics	Desktop-based VR auxiliary system	The system of linear equations in three unknowns was used as the learning content	The system of linear equations in three unknowns was used as the learning content

Table 7. Continued

Authors	Year	Title	VR hardware and software used	Math learning content	Math students' competencies that were observed/measured
Hsu	2020	Exploring the learning motivation and effectiveness of applying virtual reality to high school mathematics	Geometric objects created by Unity and 3Ds Max and operated on HTC VIVE.	"High school mathematics 2-3 systems of linear equations in three variables."	Operations and algebraic thinking
Lai et al.	2016	Geometry explorer: facilitating geometry education with virtual reality	Samsung Gear VR HMD	Geometry	Spatial understanding in geometry
Naranjo et al.	2020	An immersive teaching approach: Singapore method through virtual reality	Head-mounted display (company not specified)	Fraction	Meta-cognitive skill in math
Perri et al.	2021	Learning mathematics in an immersive way	A virtual world created with Unity3D	(1) The concept of link between an algebraic-set structure and its geometric representation (2) An orthogonal Cartesian space	Spatial understanding of algbraic function
Shi et al.	2022	The effect of game-based IVR learning environment on learning outcomes: designing an intrinsic integrated educational game for pre-class learning	IVR (company not specified)	Math (first, the graph of quadratic functions is a parabola similar to the trajectory of a flying rock)	Abstract and complex knowledge in quadratic functions, problem-solving skills, critical thinking
Su et al.	2022	Study of virtual reality immersive technology enhanced mathematics geometry learning	Virtual reality immersive learning mathematics geometry system (company not specified)	Knowledge and concepts of mathematical geometry (mathematics geometry system to enhance students' sensory experiences about mathematical geometry concepts)	Knowledge of geometry, mathematics geometry system to enhance students' sensory experiences about mathematical geometry concepts

meaningful learning experiences for their students.

Fourth, while IVR has the potential to captivate students' attention and foster immersive learning experiences, it also presents challenges related to potential distractions and disruptions (Guerrero et al., 2016). Students may become overly engrossed in the immersive environment, leading to reduced focus on instructional content. Teachers and designers need to consider ways to carefully manage IVR-based learning experiences with minimizing distractions to keeping students engaged and focused.

Fifth, designing high-quality, curriculum aligned IVR content presents another challenge in mathematics education (Christopoulos et al., 2024). Creating interactive and engaging VR experiences that effectively convey mathematical concepts, promote active learning, and allow for meaningful interactions can be resource-intensive and time-consuming. Furthermore, ensuring that IVR experiences are pedagogically sound and aligned with instructional goals necessitates collaboration among educators, instructional designers, and VR developers (Shi et al., 2022). It naturally connects to the issue of content generation, which demands scalability of IVR-supported learning platforms.

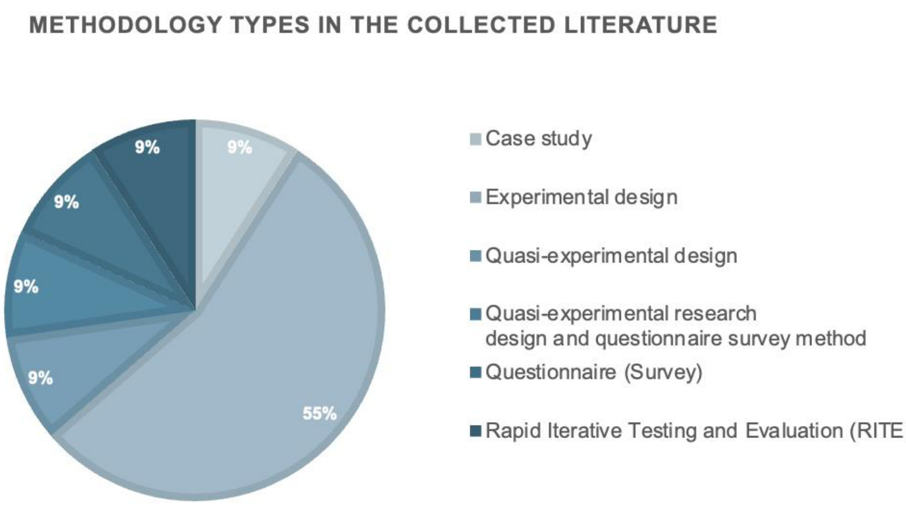

Figure 2. Methodology types in the collected literature.

To address the challenges of integrating IVR into mathematics education, a multifaceted approach is necessary. Student-centered design principles should guide the creation of IVR experiences, ensuring engagement and personalized learning experiences (Gwee, 2013). Professional development programs are essential for providing teachers with the skills and confidence they need to effectively use IVR tools in the classroom (Chen, 2012). Equity initiatives should aim to reduce disparities in access to IVR technology among students from different socioeconomic backgrounds (Naranjo et al., 2020). Technical support and infrastructure upgrades are crucial to overcome technical challenges and ensure seamless integration of IVR into educational settings (Perri et al., 2021). In addition, preparing for teacher training and supporting resources needs to be considered to help educators align IVR experiences with curriculum standards and learning objectives (Shi et al., 2022).

Our analysis indicates that among a total of 11 studies (Table 7), six (55% of the studies) focused on employing IVR technology in mathematics education using an experimental research approach (Hsu, 2021; Shi et al., 2022; Su et al., 2022). Then, the rest of the studies employed a case study (Naranjo et al., 2020), quasi-experimental design (Christopoulos et al., 2024), quasi-experimental research design and survey method (Hsu, 2020), survey method only (Perri et al., 2021), and Rapid Iterative Testing and Evaluation (Rai et al., 2016), as illustrated in Figure 2. Overall, most studies in this field have been geared towards exploring the relationships and effects of IVR technologies on secondary mathematics. This highlights the importance of conducting rigorous research in this area to explore the potential of IVR technology as a tool to enhance the quality of mathematics education.

Discussion

1. RQ1: How Does IVR Technology Enhance High School Students' Mathematics Competence?

The narrative literature review demonstrates that IVR technology significantly enhances high school students' mathematics competence, particularly in areas such as spatial awareness, operations, algebraic thinking, and complex knowledge in quadratic functions. This enhancement is primarily attributed to the immersive nature of IVR, which offers interactive and engaging learning experiences. Game-based scenarios and interactive animations within IVR environments captivate students' interest, fostering deeper understanding and participation (Naranjo et al., 2020; Perri et al., 2021). Such IVR-supported learning environments, explained by the TPACK framework, underline the synergy between teachers' capabilities and engaging digital platform for effective mathematics education (Fragaki et al., 2020; Hayes et al., 2021).

2. RQ2: What Pedagogical Strategies Did Teachers Utilize in Implementing IVR in High School Mathematics Education?

We found that the integration of IVR in high school mathematics education is supported by several pedagogical strategies, as evidenced by the literature. Teachers have successfully utilized game-based scenarios, interactive animations, and immersive 3D stimuli to boost students' engagement and learning experiences. These strategies not only enhance enjoyment and motivation but also offer diverse VR settings that foster students' active exploration and interaction (Su et al., 2022; Hsu, 2021). Moreover, the incorporation of these techniques within the TPACK framework highlights the pivotal role of teachers' pedagogical expertise in successfully integrating technology into the classroom. This integration is instrumental in advancing mathematics education by utilizing innovative technologies to complement conventional teaching methods (Koehler & Mishra, 2009).

3. RQ3: What Are the Pedagogical Factors that Need to be Considered When Creating Math Lessons Using IVR?

The review result explored that creating math lessons using IVR requires careful consideration of various pedagogical factors to ensure the effectiveness of the learning experience. Key design elements highlighted by Xu and Ke (2016) include intuitive game controls, interaction interfaces, and a user-friendly design to facilitate easy engagement with the content. Additionally, incorporating a reward system and immersive audio-visual elements can enhance engagement and immersion, contributing to a dynamic educational experience (Xu & Ke, 2016; Oprean & Balakrishnan, 2020). Considering students' diverse learning-related profiles and teacher resources, it is critical to tailor the design and delivery of IVR mathematics lessons to each student's specific learning needs. However, it is essential to acknowledge the inherent challenges associated with IVR, such as limited access to social interactions. This limitation can significantly affect the collaborative and interactive aspects of learning, which are vital for student engagement and knowledge construction. In addition, addressing curriculum alignment is imperative to ensure that IVR math lessons effectively cover core curriculum materials (Araiza-Alba et al., 2022; Garrison et al., 2000; Jones & Issroff, 2005; Tu & McIsaac, 2002; Zahn et al., 2021). This alignment is critical not only for consistency across educational tools but also for the credibility and acceptance of IVR as a viable learning platform.

Implications, Future Research, and Conclusion

The study's findings emphasize the significance of customizing IVR experiences to align with student personality traits (Shi et al., 2022). Educators are encouraged to consider factors such as extraversion when crafting IVR learning environments, recognizing that specific designs may be better suited to extrovert students (Feng et al., 2024). Personalized approaches to IVR integration can enhance student engagement and learning outcomes by aligning the technology with individual preferences and characteristics. The highly engaging nature of IVR captivates students' attention and fosters active participation during learning activities. By creating stimulating IVR environments that incorporate game-based elements and interactive simulations, educators can cultivate a positive learning environment that motivates students to actively participate and pursue mathematical understanding (Oprean & Balakrishnan, 2020).

The findings also indicate the potential of IVR technology to facilitate the development of spatial visualization skills among high school students (Gwee, 2013). By integrating IVR into instruction through game-based scenarios and interactive animations, educators provide students with opportunities to explore and manipulate geometric concepts in a virtual environment. This hands-on approach to learning promotes spatial reasoning and enhances students' ability to visualize and understand complex geometric relationships (Lin & Chen, 2016). However, ensuring the primary educational objectives are met is essential (Reimers & Chung, 2019). Therefore, educators should carefully design IVR experiences that blend game elements seamlessly with the teaching of abstract concepts, ensuring that the gameplay enhances learning outcomes rather than detracting from them (Landers et al., 2017).

Despite the promise of IVR, there is a need for more experimental studies that examines the effects of IVR across specific mathematical topics or grade levels. This investigation aligns with the study by Merchant et al. (2014), which emphasizes the importance of conducting controlled experiments to evaluate the efficacy of IVR interventions in mathematics education. Researchers can provide empirical evidence for the impact of IVR technologies on student learning outcomes by employing experiments that systematically manipulate variables such as VR exposure levels and mathematical content design. Also, studies such as Zhong et al. (2022) highlight the importance of conducting targeted investigations on the effectiveness of VR interventions across grade levels, considering cognitive development and learning readiness differences among students.

Providing professional development opportunities for teachers is essential for the successful integration of IVR into mathematics instruction (Naranjo et al., 2020). Educators require training and support to effectively use IVR tools, develop instructional strategies, and align IVR experiences with curriculum standards. By investing in teacher readiness and professional development, educational institutions can ensure that educators are equipped with the skills and knowledge needed to harness the potential of IVR technology for enhancing mathematics education.

Future research should investigate the best design principles, integration strategies, and pedagogical approaches for IVR in mathematics education. Practical considerations such as teacher training and curriculum alignment are critical to successful implementation. Longitudinal studies could examine IVR integration's long-term effects on students' math skills and academic performance. Furthermore, research efforts should be directed toward developing inclusive IVR solutions that address accessibility concerns and reduce disparities in access to VR equipment among students from various socioeconomic groups. More research is needed to identify the best pedagogical strategies for incorporating IVR into mathematics instruction, including experimenting with different instructional approaches, assessment methods, and learning activities to maximize the educational benefits of IVR.

IVR is promising for improving high school students' mathematics competence. Personalized approaches to IVR integration can lead to increased engagement and understanding of mathematical concepts. Educators can provide students with the mathematical skills required for success in the twenty-first century by utilizing IVR technology to facilitate the teaching of complex mathematical concepts and develop spatial visualization skills. Continuous research and innovation in IVR technology and pedagogy are critical to disclose its full potential for transforming mathematics education and preparing high school students for future challenges. More research is needed to improve instructional integration approaches and overcome existing barriers to inform future practices and contributions.

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Conflict of Interest

The authors declare that they have no competing interests.

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