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Challenges and Limitations of Implementing Virtual Reality in K-12 Mathematics Education

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Abstract

This study critically examines the use of Virtual Reality (VR) in K-12 mathematics education, focusing on three key areas: the challenges of implementing VR, its impact on student engagement and learning outcomes, and the barriers to its adoption. The review uncovers significant issues such as potential gaps in conceptual understanding, distractions from learning objectives, lack of established standards and evaluation criteria, and the need for extensive teacher training. While VR can enhance learning interactivity, the evidence of its educational impact is varied. The study also highlights the high costs of VR equipment and content development, and the technical complexities of implementation, as major hurdles. The study concludes that while VR has the potential to enrich mathematics education, it is crucial to address these challenges to fully realize its benefits. This includes developing affordable VR solutions, establishing clear evaluation standards, and providing comprehensive training and support for educators to ensure successful integration into the classroom.

Keywords: *Virtual Reality (VR), Mathematics Education, Student Engagement, Technical Challenges, Cost Barriers.*

INTRODUCTION

Virtual reality (VR) has radically shifted the teaching and learning experience. Unlike traditional forms of learning, students no longer rely on chalks, dusters, or other teaching aids, but instead utilize VR tools, which significantly diverge from vast educational psychology principles. VR is being used in many subjects such as mathematics, where experimental advancements have been observed (Al-Amri, Osman, & Musawi, 2020). The research utilizes a quantitative method, employing questionnaires to investigate the role of VR educational tools in mathematics education as perceived by teachers and students. Views from veteran trainers with experience using VR teaching tools were also incorporated to improve the tools. The results reveal significant potential benefits for students from this teaching method, showing that VR tools engender more interactive learning experiences for both students and teachers.

Background and Rationale

Traditionally, teaching methods implemented in classrooms today are generally print-based. Discrepancies in teaching styles between school and cultural backgrounds can lead to increased dropout rates among minority students, particularly in mathematics courses (Alarcón & Zavala, 2012). Students often exhibit math phobia, dislike, and anxiety towards mathematics, resulting from passive engagement in solving mathematical problems (Arici et al., 2019). The traditional lecture method in teaching is generally teacher-centred and often limited by time and available teaching tools.

Traditional education has continued to play a significant role in teaching mathematics selectively, leading to boredom among both teachers and students due to materials from traditional instructional methods. VR can enhance teaching experiences by allowing students to interact in an immersive "physical" environment rather than a passive "print" environment. VR engages students in exploratory learning and enriches learning outcomes by enhancing memory retention. The ability to manipulate objects in a 3D environment can improve spatial manipulations during problem-solving and allow real-time interaction with mathematical and scientific problems (August et al., 2016).

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Understanding Virtual Reality (VR) in Education

Initially, VR technology was limited to producing simulations from narrow, rigid, and predictable learning contexts. However, with advancements in computer processing, VR now includes 3D objects, spatial abilities, abstract representation, virtual manipulation, interaction, communication, co-presence ability, interaction with others, and navigation (Broisin et al., 2017). VR can recreate an environment that simulates physical presence, enabling learners to interact and feel the scenario behind it. VR's applications have pedagogical and practical implications, particularly in simulations that started with flight simulators and now encompass complex models in various fields, including mathematics.

Definition and Components of VR

Research highlights the need for good teaching methodology and student motivation in mathematics (Buentello-Montoya et al., 2021). Linking mathematics teaching to literacy is essential for achieving academic needs. New tools and attractive classroom methodologies, such as VR, are preferred choices for active and participative teaching methods. VR, defined as the use of computer technology to create simulated environments that can simulate physical presence, has great potential in education (Cheng & Tsai, 2020). A study based on a descriptive quantitative methodology with a sample of 257 students showed a strong preference for learning diversified mathematics in VR environments. The transformative power of VR in learning is substantial, engaging, stimulating, and enjoyable (Chou et al., 2001).

Benefits of VR in Education

Based on action and learning, VR technology is well-suited to contemporary students who spend much of their free time in complex technological environments. Studies have shown that VR environments effectively reduce difficulties in visualizing abstract concepts and perceiving relationships among topic elements in physics education (Chuah, 2019). VR helps students establish perception and action relationships with objects in abstract concepts, enhancing understanding through interactive and user-friendly structures (Cowling & Birt, 2018).

Integration of VR in Teaching Mathematics

The impetus of learning has shifted from an evocative learning environment to an invigorating teacher who shifts students' focus to subject-related concept formation. Despite VR's support, a teacher's active participation is needed. Effective utilization of VR in classrooms shapes learner motivation to accept, experiment, explore, and construct knowledge (Dodevska & Mihic, 2018). Pre-service teacher education courses should include VR operations and effective usage methods. Teachers play a crucial role in the learning process, shaping intentions for learning and transforming hesitations into enthusiasm and excitement (Donkin & Kynn, 2021).

Study Purpose

The purpose of this study is to investigate the role of Virtual Reality (VR) as a learning tool in teaching mathematics in schools. Specifically, this research aims to explore how VR can enhance student engagement, improve comprehension of mathematical concepts, and foster critical thinking and lifelong learning skills. By examining the experiences of teachers and students using VR in the classroom, the study seeks to identify the benefits and challenges of integrating VR into mathematics education. Through quantitative and qualitative analysis, this research will provide insights into the effectiveness of VR-enhanced learning environments and offer practical recommendations for educators and policymakers to optimize the use of VR in teaching mathematics. The ultimate goal is to enhance educational outcomes and inspire a greater appreciation for mathematics among students.

Research Questions

How does the integration of Virtual Reality (VR) in teaching mathematics affect student engagement and motivation?

What impact does Virtual Reality (VR) have on students' comprehension and retention of mathematical concepts?

What are the key challenges and benefits experienced by teachers and students when using Virtual Reality (VR) in mathematics education?

Conceptual Framework

The conceptual framework for this study explores the role and impact of Virtual Reality (VR) as a learning tool in teaching mathematics in schools, integrating various educational theories to enhance student engagement, comprehension, and critical thinking see figure 1.

Theoretical Foundations

Constructivist Learning Theory: This theory suggests that learners build their understanding through experiences and reflection. VR supports this by providing immersive environments where students can interact with virtual objects, enabling active knowledge construction.

Flow Theory: Introduced by Csikszentmihalyi, flow theory describes a state of complete immersion in an activity. VR can induce this flow state by creating engaging and immersive educational experiences, enhancing motivation and learning outcomes.

Human-Computer Interaction (HCI): HCI principles emphasize intuitive and immersive interfaces between people and computers. VR's user-centered design enhances the learning experience, promoting deeper cognitive and emotional involvement.

Components of the Framework

VR Technology and Tools

Hardware: Includes VR headsets, gloves, and other peripherals. High-quality tools are crucial for effective VR learning experiences.

Software: Educational VR applications that align with the mathematics curriculum, providing interactive and engaging content.

Learner Engagement and Immersion

Engagement: VR enhances engagement by offering visually stimulating environments that capture students' interest.

Immersion: VR's immersive nature allows students to experience mathematical concepts tangibly, leading to deeper cognitive involvement.

Learning Outcomes

Knowledge Retention: VR's experiential learning improves retention by making learning more memorable.

Understanding of Complex Concepts: VR aids comprehension by allowing visualization and manipulation of abstract concepts.

Problem-Solving Skills: Interactive simulations in VR enhance critical thinking and problem-solving by presenting real-world scenarios.

Accessibility and Inclusivity

Equity of Access: Ensuring all students have access to VR technology, addressing potential barriers.

Inclusive Design: Designing VR experiences accessible to students with disabilities, accommodating diverse learning needs.

Educational Practices and Integration

Curriculum Integration: Strategies for incorporating VR into curricula, aligning with educational standards.

Teacher Training: Professional development for educators to effectively use and integrate VR technology into teaching practices.

Relationships between Components

VR Technology and Engagement/Immersion: High-quality VR systems engage students and immerse them in the learning process, enhancing educational outcomes.

Engagement/Immersion and Learning Outcomes: Increased engagement and immersion lead to better retention, understanding, and problem-solving skills.

Accessibility and Learning Outcomes: Ensuring accessibility and inclusivity leads to more equitable educational outcomes.

Educational Practices and Learning Outcomes: Effective integration of VR and proper teacher training are essential for maximizing the benefits of VR in education.

Figure 1: Conceptual framework diagram illustrating the role and impact of Virtual Reality (VR) in teaching mathematics

Literature Review

Importance of Virtual Reality in Education

Virtual reality (VR) has revolutionized the educational landscape by offering immersive, interactive, and engaging learning experiences. VR's potential to enhance learning outcomes has been demonstrated across various educational settings, including STEM (Science, Technology, Engineering, and Mathematics) subjects, where traditional teaching methods often fall short (Al-Amri et al., 2020). VR's immersive environments can make abstract concepts more concrete and accessible, fostering a deeper understanding and retention of complex subjects like mathematics and physics.

The Role of VR in STEM Education

Research highlights the effectiveness of VR in improving students' motivation and achievement in subjects like physics (Al-Amri et al., 2020). The integration of 3D-VRLE (3D Virtual Reality Learning Environment) has significantly enhanced Omani eighth-grade students' performance and interest in physics. Similarly, Arici et al. (2019) have identified research trends in augmented reality and VR, emphasizing their growing use in science education to provide interactive and engaging learning experiences that traditional methods cannot offer.

Impact of VR on Student Engagement and Learning Outcomes

Several studies underscore the positive impact of VR on student engagement and learning outcomes. For instance, Broisin et al. (2017) describe Lab4CE as a remote laboratory for computer education that uses VR to provide hands-on learning experiences. The study found that such immersive environments can significantly enhance students' understanding and retention of complex concepts. Similarly, August et al. (2016) highlight the Virtual Engineering Sciences Learning Lab, which provides STEM education a second life through VR, thereby increasing student engagement and achievement.

Technological Advancements and VR Implementation

The rapid evolution of VR technology has expanded its applications in education. Cheng and Tsai (2020) explore how students' motivational beliefs, strategies, and perceived immersion impact their attitudes towards science learning with immersive VR. They found that VR environments significantly enhance students' motivation and learning outcomes. This is further supported by Chuah (2019), who discusses the adoption of extended reality technologies and their future research agenda, emphasizing the role of VR in transforming educational practices.

Challenges and Barriers in VR Integration

Despite the promising benefits, integrating VR into education comes with challenges. Donkin and Kynn (2021) evaluate the learning space's impact on active learning in a technology-rich collaboration studio, highlighting the importance of infrastructure and support in successful VR implementation. Similarly, Cowling and Birt (2018) emphasize the need for a design-based research approach to enhance skills development using mixed reality in paramedic science, pointing out the necessity of pedagogical adjustments and teacher training for effective VR integration.

Benefits of VR in Experiential Learning

One of VR's most significant advantages is its ability to create experiential learning environments. According to Dodevska and Mihic (2018), VR technologies in project management provide hands-on experience that can be crucial for understanding complex processes. Frost et al. (2020) further supports this by demonstrating that VR can create engaging and interactive learning environments that significantly enhance students' learning experiences.

Developing Spatial and Kinesthetic Intelligence through VR

The use of VR in education also aids in developing spatial and kinesthetic intelligence. Güney (2019) discusses the role of visual literacy and visualization in instructional design, highlighting how VR can help students better understand and retain information through immersive, interactive experiences. This is echoed by Buentello-Montoya, Lomelí-Plascencia et al. (2021), who emphasize the role of reality-enhancing technologies in teaching and learning mathematics, particularly in fostering spatial reasoning and problem-solving skills.

METHODOLOGY

To explore the challenges and limitations of using Virtual Reality (VR) in mathematics education, a systematic literature review (SLR) was conducted. This structured approach helped identify, evaluate, and synthesize relevant research studies, providing a comprehensive understanding of the current state of VR in mathematics education.

The systematic review aimed to answer three key research questions: (1) What are the documented challenges and limitations of implementing VR in mathematics education? (2) How effective is VR in enhancing student engagement and learning outcomes in mathematics? (3) What are the technical and cost-related barriers to the widespread adoption of VR in mathematics education?

A comprehensive search strategy was employed, targeting databases such as Google Scholar, ERIC (Education Resources Information Center), IEEE Xplore, SpringerLink, and ScienceDirect. Search terms included "Virtual Reality in mathematics education," "VR challenges in education," "VR limitations in K-12 mathematics," "Educational technology and VR," "Cost of VR in education," and "Effectiveness of VR in STEM education." The inclusion criteria focused on peer-reviewed journal articles, conference papers, and book chapters published between 2010 and 2023, specifically addressing the use of VR in K-12 mathematics education. Studies that did not meet these criteria, such as those focusing on higher education or non-mathematics subjects, were excluded.

The study selection process involved an initial screening of titles and abstracts to identify relevant studies, followed by a full-text review to ensure they met the inclusion criteria. Duplicates were removed, and irrelevant studies were excluded. Data extraction was conducted using a standardized form to collect information on authors, publication year, study aims, research methodology, key findings, and issues related to challenges, limitations, effectiveness, and technical and cost-related barriers.

Data synthesis was performed using a narrative approach, identifying common themes and patterns across the studies. The findings were organized into three main categories: challenges and limitations of VR in mathematics education, effectiveness of VR in enhancing student engagement and learning outcomes, and technical and cost-related barriers.

RESULTS

Current Practices and Examples

Many VR applications promise significant educational benefits. The increasing deployment of VR in pedagogical contexts has witnessed the creation of different VR examples, many of which are tangible experiences that cannot be obtained through traditional educational methods. This approach has proven to be very effective for STEM (Science, Technology, Engineering, and Mathematics) and experimental sciences in general. In particular, interdisciplinary experts use VR in collaboration with teachers to provide students with a unique educational framework to develop problem-solving skills by facing open questions and creativity, often through design problems. However, VR applications are still rather limited in the field of school teaching and are mainly intended for use during occasional experiences. Indeed, it is interesting to note that despite the existing critical mass of positive educational VR experiences and strong incentives for its use, during school daily practice, the common equipment of the classroom rarely includes VR headsets due to costs. It is foreseeable that this situation could change in the near future due to the increasingly wider commercial availability of low-cost viewers that are capable of providing VR experiences that are good enough for educational purposes.

Figure 2: *current practices and examples of using VR in mathematics education*

Figure 2 illustrates current practices and examples of using VR in mathematics education. It shows students using VR headsets to solve mathematical problems with virtual manipulatives like 3D graphs, geometric shapes, and interactive number lines. The teacher guides the engaged and focused students in a classroom equipped with mathematical posters and materials.

Challenges and Limitations of Using VR in Mathematics Education

Using VR in mathematics education presents several challenges and limitations. One major issue is the risk of creating gaps in conceptual understanding. While VR can make learning engaging and interactive, students might focus more on the virtual experience rather than the underlying mathematical concepts, leading to a superficial understanding. Additionally, VR's engaging nature can sometimes distract students from their learning objectives if not properly managed. Without adequate supervision, students may misuse VR for entertainment rather than educational purposes.

Another significant challenge is the lack of established standards and evaluation criteria for VR in K-12 mathematics education. This absence of benchmarks makes it difficult for educators to assess the quality and effectiveness of VR content, leading to inconsistent implementation. Moreover, the high costs associated with developing and producing VR content, as well as purchasing and maintaining the necessary hardware, pose a substantial financial burden on educational institutions. Many schools, especially those in underfunded areas, may struggle to afford the equipment required for VR, exacerbating educational inequalities.

VR systems also require complex technology, including high-performance computers, headsets, input devices, and tracking systems. The technical complexity and the need for specialized expertise to set up and maintain these systems further complicate their implementation. Many teachers lack the technical training and support needed to effectively integrate VR into their teaching practices, necessitating professional development and ongoing assistance(Tashtoush et al., 2023b; Wardat et al., 2024).

Lastly, the immersive nature of VR can increase the risk of cyberbullying and misuse. Ensuring that students use VR responsibly and safely requires careful monitoring and strict usage guidelines. Addressing these challenges will require significant investment in affordable VR technology, development of clear standards and guidelines, and collaborative efforts to share resources and expertise among educational institutions.

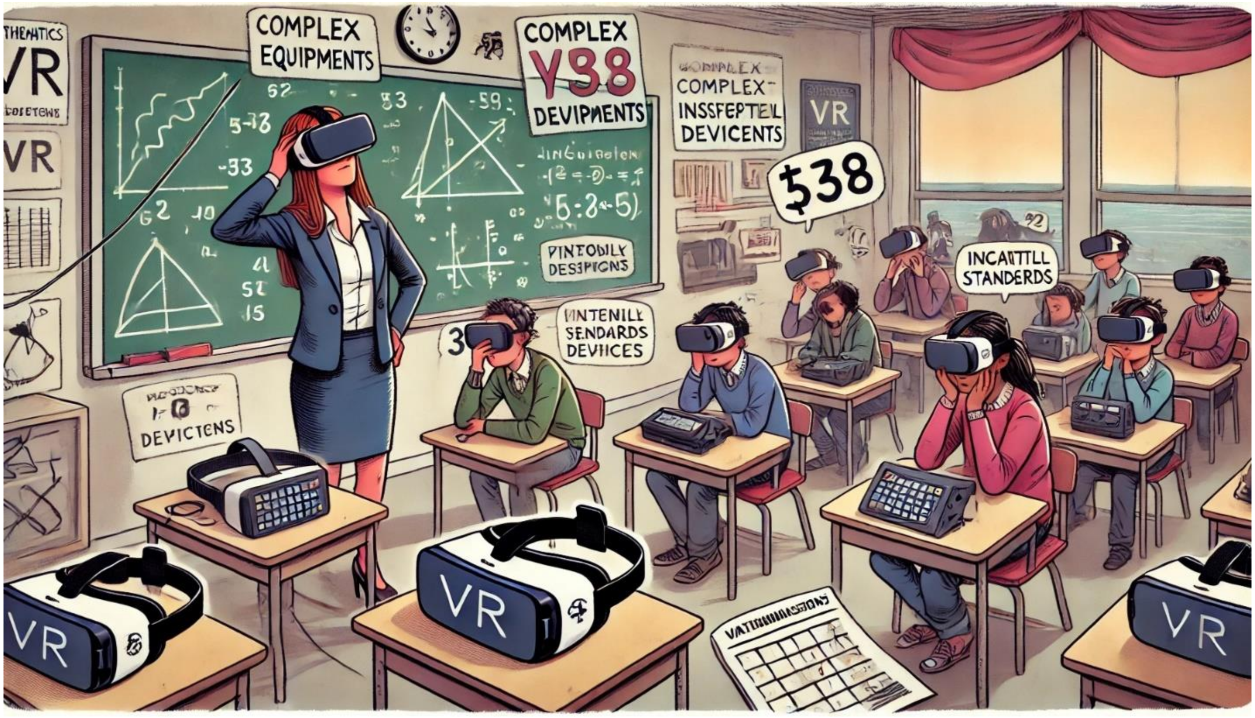

Figure 3: challenges and limitations of using VR in mathematics education

Figure 3 is an image illustrating the challenges and limitations of using VR in mathematics education. It depicts a teacher struggling with VR equipment while some students appear confused and distracted. Visible price tags highlight the high costs, and the teacher's confusion with a manual indicates the lack of standards and training. In the background, students are waiting due to insufficient devices.

Technical and Cost-related Challenges

Currently, standards do not exist for what constitutes an effective educational VR system for use in computer-enabled STEM learning. Although general rubrics for evaluating technology-appropriateness for mathematics teaching exist, there are no general guidelines for how to evaluate VR for use in the K-12 mathematics classroom. Since educators and developers do not have the benchmark standards or frameworks to measure the value and quality of virtual experiences, almost any VR content is seen as good. Development and production costs are also high. Unlike using other digital tools, VR promises some unique educational features. Although students may learn some aspects of a topic more quickly than they would without VR, studies have yet to demonstrate that students who use VR initially achieve better understanding in mathematics(Abu Nasser & AlAli, 2022; AlAli & Abunasser, 2022; Al-Barakat et al., 2022; Saleh & AlAli, 2022).

VR requires complex technology such as headsets, input devices, or tracking software and processing equipment with significant memory and quick responses in order to produce high-fidelity 3D graphics and be experienced as a realistic simulation. In education, a possibly large number of learners need to experience the VR tool, not only potentially increasing the costs, but also making VR difficult to implement in all education settings. With respect to the teaching of mathematics, which is an inherent part of the curriculum in most countries, VR needs to be embedded into the regular use in order to be useful. In the majority of schools, where teachers may not have much technical training and where access to high-performance computer equipment may be limited, deploying VR is a significant challenge that can only be solved by collective sharing of resources(Stoica & Wardat, 2021; Alneyadi et al, 2022b).

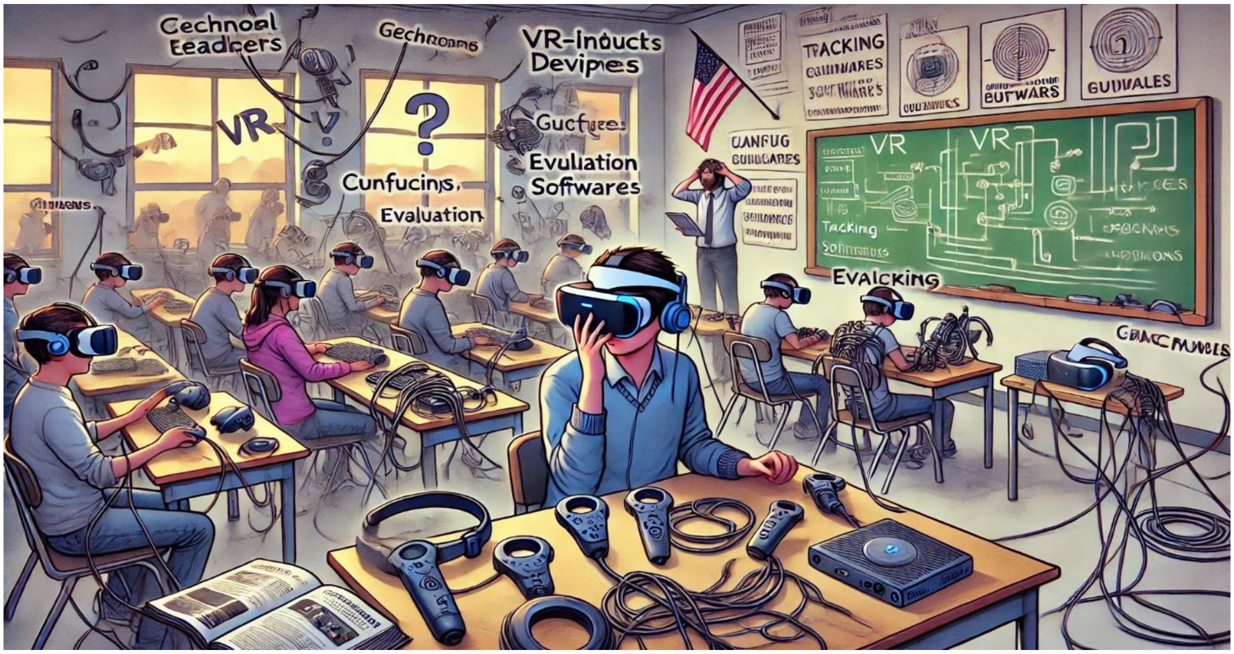

Figure 4: Technical and cost-related challenges of using VR in education

Figure 4 illustrates the technical and cost-related challenges of using VR in education. It shows a teacher struggling with complex VR equipment while students wait due to insufficient devices. The visible price tags highlight the high costs, and the teacher's confusion with guidelines emphasizes the lack of standards and evaluation criteria.

FUTURE DIRECTIONS AND RECOMMENDATIONS

The role of VR in this process can be internalized and added to complement and enrich AR-enhanced teaching and learning since these models can be synergistic and complementary. The authors of this article are currently working on a project to validate a multimodal VR and AR approach to STEAM education in basic and secondary schools, which also takes into account the constraints imposed by educational policies in Portugal and perception by conducting action research studies. This approach can, in a synergistic way, support the lifelong learning process through intentional interventions carried out in formal, non-formal, and informal educational contexts and also support students in their learning processes using collaborative pieces for each phase of the teaching and learning process(Zakariya & Wardat, 2023; Jarrah et al., 2022b).

In order to prepare for the challenges of the future and to guide these actions, institutional training projects with common goals and actions articulated with internal and external educational communities are needed. It is crucial to implement educational projects that also build an evolutionary model of the various entities that are part of educational systems. Through high-quality research based on critical, reflective, and shared thinking of all parties involved in this process, the process must evolve, supported by evidence-based educational practice(Hidayat & Wardat, 2023; Tashtoush et al., 2023a; Alneyadi et al, 2022a; Jarrah et al., 2022a; Wardat et al., 2021).

It is necessary to advance with models that are favorable to the development of soft skills, as well as models that are inclusive, adjusted to the characteristics of the different domains, flexible, adaptable, and supportive of different learning contexts and situations in the face of diverse challenges and difficulties, considering the unpredictability and rapid change in global environments.

Educational institutions are at an important crossroads, given that the repercussions of the COVID-19 pandemic are expected to significantly influence how educators work. It is now necessary to thoroughly review the existing situation to update and review formation processes and institutional educational policies. It is necessary to reflect on classroom models and teaching and learning practices that are more grounded in effective, meaningful learning processes, particularly in the context of Science, Technology, Engineering, Arts, and Mathematics (STEAM) education(Wardat et al., 2022; Jarrah et al., 2020; Gningue et al., 2022; Tashtoush et al., 2022).

CONCLUSION

The systematic literature review highlights several challenges and limitations of using VR in mathematics education, including potential gaps in conceptual understanding, distraction, lack of standards, and high costs. While VR has the potential to enhance student engagement and learning outcomes, its effectiveness varies. Addressing these challenges will require investment in affordable VR technology, development of evaluation standards, and adequate teacher training. By overcoming these obstacles, VR can become a valuable tool in mathematics education, providing students with engaging and immersive learning experiences.

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