Emerging Trends in VR for Science Education

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Abstract

Virtual Reality (VR) transforms science education by providing immersive, interactive environments that enhance student engagement and comprehension of complex concepts. Immersive environments in VR offer cost-effective alternatives to traditional labs, enhance teacher preparation by bridging theoretical knowledge and hands-on experience, and equip educators with innovative instructional strategies. Here, we explore emerging trends in VR applications for science education, emphasizing its integration into preservice teacher preparation and classroom instruction. Drawing from observations at a Florida-based virtual charter school, we examine how VR facilitates experiential learning through tools like 360° models, interactive simulations, and gamified tasks. PSTs observed high levels of student engagement, suggesting VR's potential to motivate learners across diverse contexts. The article highlights VR's alignment with constructivist pedagogies, enabling students to actively explore the application of technology during science instruction. The body of research available and our observations underscore the necessity of ongoing technological and curricular advancements to optimize VR's impact on science education. Teaching with VR fosters critical thinking, problem-solving, and engagement in STEM disciplines.

Introduction

Upon entering a sixth-grade science classroom at Virtual Reality Academy (VRA), ten preservice teachers observed the teacher's avatar in a virtual reality environment, engaging about 20 student avatars in a discussion about water. The teacher's avatar stood in front of an outdoor Virtual Reality classroom environment, and student avatars were seated in groups at various tables. After a short discussion, the teacher's avatar instructed the student avatars to spend the next 10 minutes exploring the resources in the Virtual Reality environment. The environment consisted of resources like a meteorologist avatar with a short, prerecorded message about different types of precipitation, a screen with a short text about evaporation, a short video about hurricanes, and a display about water runoff and flooding. Students were then summoned back to their group tables, where the teacher's avatar directed them to gather around the water cycle model nearest their table and talk about what was happening. The preservice teachers observed the teacher's avatar listening to each group and asking assessment questions such as: What observations have you seen that support this stage of the water cycle?" and "What might happen to the cycle if evaporation decreases?" All assessment question prompts help to gauge understanding and guide student thinking. Next, the teacher permitted the students to use a 3D pen and asked them to label and annotate the model to illustrate the water cycle. The preservice teachers noticed the teacher's avatar visiting each group of student avatars, asking advancing questions, and instructing groups to record an explanation of the water cycle. While groups recorded their water cycle explanation, the preservice teachers exited the VR classroom environment.

VR in Education: Opportunities, Challenges, and the Road Ahead

Ivan Sutherland and Bob Sproull pioneered the "Sword of Damocles," the first Virtual Reality (VR) and augmented reality (AR) system, in 1968, marking the inception of VR (Sutherland, 1968). Initially limited to military and industrial applications, VR technology entered the commercial sphere in the 1980s with the advent of head-mounted displays (HMD) pioneered by companies like VPL Research and NASA (Blascovich & Bailenson, 2011). As technology continues to advance, the capabilities of VR have also made tremendous strides in recent years, positioning it for widespread adoption in education (Elmqaddem, 2019).

The field of education is now exploring VR's potential across disciplines, particularly in science education, where interactive simulations can model complex processes and enhance student engagement (Lin et al., 2024). As VR technology progresses, many researchers posit that VR is transforming into a highly effective educational tool for experiential learning. Educational institutions considering VR must carefully inform preservice teachers about its use, provide adequate preparation, and set realistic expectations regarding VR's effectiveness (Shen et al., 2019). While some studies assert that VR is ready for implementation (Elmqaddem, 2019), continuous improvement remains necessary, particularly in content development, cost-effectiveness, and pedagogical integration.

As the use of VR in science education grows, there is a pressing need for robust and practical assessment methods suited to these immersive environments. Traditional assessment strategies, often employed in classroom-based settings, may not adequately capture learning outcomes in VR due to the dynamic, interactive nature of these environments (Udeozor et al., 2023). Several innovative assessment frameworks have emerged to address this gap, including stealth assessment embedded within the virtual environment (Alcañiz et al., 2018). Stealth assessment uses data from student interactions within the VR setting to evaluate competencies in real-time, relying on the evidence-centered design (ECD) framework. Stealth assessment's indirect, non-intrusive method allows students to be assessed without disrupting their engagement, an essential feature in VR environments where immersion and flow are key to achieving learning outcomes. Tasks are designed to elicit observable behaviors that align with specific learning goals, providing measurable evidence of student knowledge and skills. Similarly, the Game-Based Assessment Framework (GBAF), also grounded in the ECD framework, ensures that VR assessments are authentic, challenging, and reflective of real-world tasks by aligning objectives, outcomes, game tasks, and scoring metrics (Udeozor et al., 2023). The GBAF facilitates a multi-dimensional approach to assessment, which is especially useful in environments that require higher-order cognitive skills like problem-solving and critical thinking.

While VR offers exciting possibilities for science education, it also presents several health and safety concerns. For instance, Sun et al. (2019) reported that taller VR users are at a greater risk of postural instability due to the design of head-mounted displays (HMDs), which may affect their balance. However, their study did not include a comparative analysis with traditional instructional methods, leaving room for further research to investigate how VR’s physical demands differ from standard classroom activities. Additionally, concerns about motion sickness, eye strain, and prolonged engagement in immersive environments suggest that VR should be carefully integrated into curricula, with user health as a top priority (Hirzle et al., 2022).

The full potential of VR is still not entirely understood in the context of its educational uses. As VR technology advances, Sharrab et al. (2023) theorized that it could evolve into a comprehensive classroom management system where students log into virtual classrooms, access course materials, and establish connections similar to traditional face-to-face interactions. VR holds potential beyond content delivery—possibly altering how we think about school infrastructure and student-teacher interaction. Diffusion of innovation (DOI) theory provides a framework for understanding how new technologies, such as VR, are adopted and implemented within educational environments. According to this theory, the adoption process follows a predictable pattern where early adopters and innovators first experiment with the technology while most users wait to assess its effectiveness. Additionally, the theory emphasizes factors such as relative advantage, compatibility, complexity, trialability, and observability as key elements influencing the adoption process of innovations (Rogers, 2003). Classroom technology integration based on DOI theory has shown that teachers’ willingness to integrate new technology depends on several educator attributes, including general attitudes toward technology, attitudes toward technology in education, technological innovativeness, and general innovativeness, among others (Van Braak, 2001). As VR becomes more affordable and its benefits become more evident, its integration into education will likely accelerate. However, factors such as cost, preparation, and cultural acceptance will play crucial roles in shaping the pace of adoption, with schools gradually embracing VR as part of the broader educational landscape. This article explores the use of VR in science education, emphasizing VR integration into teacher preparation to enhance preservice teachers’ technological proficiency through real-world experience and innovative strategies.

Enhancing Teacher Readiness: Integrating VR into Science Education Preparation

Incorporating VR into preservice science teacher education holds great potential, not only as a tool for teaching students but also as a means to enhance the preparation of future educators. Teachers' willingness to adopt new technologies is often a key factor in the successful diffusion of innovations in education (Khukalenko et al., 2022), bridging the gap between theoretical knowledge and hands-on experience. Instructor observations and informal discussions with preservice teachers who observed students during VR science instruction provided valuable insights into the integration of VR technology.

Several years ago, the first author was asked to develop a technology course for preservice teachers. Nearly two decades had passed since he left teaching secondary science to pursue a career as a science teacher educator. With each passing year, the impact of technology in the classroom grew. While developing the technology course, he had an opportunity to work with Virtual Reality Academy (VRA), a pseudonym that allowed preservice teachers to observe science VR instruction. The second author is a graduate assistant, a doctoral candidate in instructional design and performance technology, and a secondary classroom teacher.

VRA is a third-to-tenth-grade charter school primarily serving students in the state of Florida and is an early adopter as a fully online VR school. Students attending VRA charter school participate in two hours of synchronous virtual reality science instruction each week and two hours of weekly asynchronous study on the Canvas platform. During VR science instruction, students first engage in a topic, such as watching a brief video clip or a prerecorded avatar introduction, followed by a short class discussion. Class discussions at VRA are facilitated by the teacher's avatar, which uses spatial audio. With the student avatars seated in groups, the teacher avatar either broadcasts to all students or moves between tables to prompt discussions. The teacher uses a mix of voice communication, virtual whiteboards, and embedded interactive prompts to guide conversation. Then, students complete an activity to explore a science concept through small group tasks using several VR instructional resources like expert recordings, 360° bubbles, interactive models, simulations, etc. Next, students are challenged to apply their understanding of the concept using VR tools like a 3D pen (used for drawing and annotating in space), immersive effects (IFX) (interactive 3D objects embedded in the VR environment), and sticky notes for placing comments and observations on virtual spaces. To mitigate health risks, the Virtual Reality Academy (VRA) limits students' time in VR to manage the physical demands of HMDs. A typical schedule includes a 20-minute break between VR sessions, with no more than 40 minutes spent in VR during any one class period. Students attend VR classes four days a week in the morning, while afternoons are reserved for asynchronous work, tutoring, and office hours with teachers. This structure helps limit students' daily VR usage to an average of 120 minutes. Additionally, one Friday afternoon each month is dedicated to a supervised VR social hour, allowing students to interact with classmates in a more relaxed, social setting.

Integrating VR into Teacher Education: A Course Overview

For two weeks in the course titled “Emerging Technology in the Classroom,” preservice teachers learn about teaching in virtual reality. The learning outcomes for this module include discussing the impact of VR technologies on education and explaining how wearables may be used to support student learning. Outside class meeting times, students are expected to complete the content module and module assignment by the end of the first week. The content module includes embedded text, videos, and a few articles on VR in educational settings. The module assignment is a short quiz and a reflection evaluating the observed VR experience.

Preservice teachers meet in person twice a week for one hour and 15 minutes during the two-week module. During the first in-person class meeting of the module, time is dedicated to students logging into the VR platform, Engage, learning how to create an avatar, signing into a session, and learning some essential VR tools like 3D virtual pens. During the second class period, preservice teachers meet in VR for a tour. Students visit various virtual locations, interact with scientific models, and learn to use additional VR tools, such as integrated web browsers and 3D visualizations. Preservice teachers observe a classroom lesson during the third- and fourth-class meeting times.

Passive to Active Learning: Preservice Teachers’ Insights on VR in Science

In their VR lesson observations, the preservice teachers considered the experience of ENGAGE VR as engaging for students because they were in and interacted with the learning environment. Students could explore scientific concepts in dynamic, immersive ways that promote active participation, which is inconsistent in traditional classroom settings. While hands-on, inquiry-based learning can and does happen in traditional classrooms, VR offers the ability to manipulate 3D models and travel virtually through space. Visualizing molecular structures in 3D or simulating planetary motion in zero-gravity environments is a level of immersion offered by VR that is difficult, if not impossible, to replicate in traditional classrooms. Preservice teachers noticed that VR transformed passive learning into an active process: students could move around, visualize scientific phenomena, and participate in hands-on activities, like gaming environments that capture users’ attention. After participating in the VR experience, many PSTs noted that students appeared more involved and engaged than when using worksheets or textbooks. Their prior experiences in traditional classrooms helped them recognize the increased engagement offered by the VR environment. Furthermore, the capacity of VR to simulate real-life experiences, such as studying the ocean to classify marine life or conducting experiments in space, made the science content more engaging and accessible.

Preservice teachers had mixed opinions regarding the grade levels for which VR is appropriate. While they felt that VR has the potential to be effective at all grade levels, they also mentioned that younger students may need extra support to use the technology efficiently. They indicated that VR would best be utilized for upper elementary through high school students due to the cognitive and technical demands of manipulating VR systems. Key factors involved device usability, possible technical glitches, and teacher control features that would help maintain order in the classroom. Interestingly, VRA involves students participating in a 40-minute VR class during the second half of the third grade. Preservice teachers also focused on how VR could be further used in conducting virtual field trips that would enable students to explore aspects of science that they may otherwise never experience.

Witnessing the use of VR in the science classroom had preservice teachers acknowledge the connection between standards and learning outcomes. They highlighted that VR promotes inquiry-based learning, in which students go through an interactive process, exploring scientific ideas interactively while reinforcing the content through experience. Teachers can design lessons accordingly, including formative assessments such as embedded quizzes, short-answer questions, and interactive discussions within the VR environment. The possibility of giving immediate feedback and monitoring student progress via digital tools is an excellent advantage for instruction. For instance, preservice teachers noticed that in subjects such as biology or physics, VR could be beneficial when dealing with topics related to molecular structures or the motion of planets by representing them as virtual 3D objects.

While observing at VRA, preservice teachers witness various VR assessment methods, such as multiple-choice questions integrated into the VR environment. In one assessment, students choose from three possible responses, with the correct answer advancing them to the next question and the incorrect ones returning them to the start while providing feedback through a prerecorded instructor avatar. Another formative assessment involves sending students a question to their virtual tablet, prompting a response. At VRA, students demonstrate learning through tasks such as identifying environmental and genetic factors affecting crops in a plant breeding lesson, which serves as a formative assessment. In a biomes lesson, students apply their understanding through a summative project, where they modify a State Park to demonstrate concepts such as forest fire succession or water filtration, providing a comprehensive way to assess learning outcomes.

The preservice teachers perceived VR as an intrinsically motivating tool because it was novel and interactive. They showed greater interest in activities that allowed customization, such as creating their avatars or exploring different virtual environments. Preservice teachers observed students' eagerness to engage in the simulation about space, as they could explore astronomy through an immersive experience. Additionally, gamification factors in VR, such as interactive challenges and collaborative problem-solving activities, were cited as reasons for sustained motivation on the part of students. Even so, preservice teachers learned the importance of providing instructions and scaffolding to ensure students focused on learning outcomes, not the magic of the technology itself.

A key affordance of VR in a classroom is the capacity to meet varied learning needs. The preservice teachers realized that ENGAGE VR offered multiple forms of interaction, including visual exploration, hands-on manipulation of virtual objects, and written or spoken communication. For example, students could engage with 3D models to better understand complex scientific concepts or use tools like virtual pens and simulations to interact with content in a more immersive and hands-on manner. Personalization also included setting a difficulty level that suited the needs of the individual and customizing virtual representations to enhance their engagement. However, the preservice teachers also recognized some potential challenges regarding access, including access to reliable internet, the affordability of devices, and concerns for students sensitive to motion.

The preservice teachers witnessed the positive impact, engagement, motivation, and accessibility of VR science instruction while supporting standards-based instruction. Their experiences highlighted that preparing future educators through practical experience in VR technology was necessary to create readiness for this resource in their teaching practice. As VR evolves, teacher preparation must offer novices knowledge and the ability to use this technology in meaningful student learning activities.

VR as a Tool for Inclusive and Experiential Science Education

One of VR's most cited advantages, also observed at VRA, is its ability to engage students and capture their attention in ways that traditional methods cannot. This reflects the relative advantage component of DOI theory (Rogers, 2003), as VR offers clear benefits over conventional teaching methods, such as increased student enjoyment and engagement (Makransky et al., 2021). Conventional teaching methods, also referred to sometimes as traditional methods, refer here to standard in-person classrooms that mostly use lectures, textbooks, and 2D materials. Although VR does not necessarily increase the amount of learning compared to other methods, it consistently enhances students' enjoyment, which is a critical factor in educational adoption. This increased enjoyment can be particularly valuable in fields like physics, where students often struggle with abstract and challenging concepts. VR's immersive experiences, which allow students to visualize and manipulate scientific concepts, reflect the compatibility between VR and the needs of modern education, particularly in disciplines that require active, hands-on learning.

Sarapak et al. (2022) found that physics teachers, especially during and after the COVID-19 pandemic, overwhelmingly expressed positive views regarding VR's ability to help students understand complex ideas. This suggests that early adopters within the education community are more likely to embrace VR as they observe its instructional benefits in action. The technology's support of constructivist learning (Jensen & Konradsen, 2018), emphasizing learning through doing, also aligns with the educational values of those seeking innovative student-centered pedagogies. Scholars such as Dewey, Lewin, and Piaget emphasize the importance of active learning approaches; VR supports immersive, experiential interaction (Schott & Marshall, 2018).

While VR does not inherently provoke learning, it serves as an effective medium for experiential learning, supporting core principles of constructivist instruction (Jensen & Konradsen, 2018). This aligns with the DOI theory's focus on innovations that can be trialed and adapted (Rogers, 2003). For example, Švedová et al. (2021) demonstrated that VR's gamification of science education promotes problem-solving and reflection, key aspects of constructivist education. The trialability of VR in classroom settings, starting with small, targeted lessons, can help educators see firsthand the benefits before committing to broader adoption.

Concerns regarding whether VR's novelty will wear off are common, as innovation often faces challenges sustaining engagement. However, VR has generated higher levels of attention, presence, and enjoyment than traditional methods (K.-T. Huang et al., 2019). This higher engagement level speaks to VR's long-term relative advantage, suggesting that while novelty may initially attract attention, the technology's continued appeal is rooted in its ability to maintain student interests. The findings by Huang et al. (2021), which show sustained engagement over multiple VR sessions, support their idea, indicating that gradual increases in immersion can help maintain high levels of involvement. Moreover, VR has been found to benefit students with learning differences, such as those with dyslexia or ADHD, by offering contextualized content and minimizing distractions (Lozano-Álvarez et al., 2023). These positive results, particularly the observed increase in student engagement, may encourage broader adoption of VR by educators, especially when supported by evidence of benefits for diverse learners. This could drive adoption within the early majority of educators, especially as VR continues to be viewed as a valuable tool for diverse learning needs.

Studies show that students prefer VR over other passive learning forms (Švedová et al., 2021). Passive learning takes place when students absorb information through lectures or reading. Juxtaposed to passive learning is active learning, where students must participate in the learning process through discussions and apply information to given contexts to solve or think about issues. Some concerns have been raised regarding the ability of VR to maintain engagement after the novelty has worn off. In a study by Huang et al. (2021) that looked at engagement, among other factors, over multiple VR sessions, motivation and engagement remained high. The researchers suggest that building up sessions from moderately immersive to highly immersive may lend itself to maintaining engagement.

Science education often faces logistical and financial constraints that limit the ability to conduct experiments or provide students with real-world experiences. VR offers a cost-effective solution by allowing students to conduct virtual experiments that mimic real-world phenomena without expensive laboratory equipment. Sarapak et al. (2022) noted that physics teachers in budget-constrained districts supported using VR as an alternative to costly in-person experiments. This approach alleviates financial burdens and opens up new opportunities for students in underfunded schools to engage with high-quality, experiential science education. Additionally, VR can simulate dangerous or ethically problematic experiments, allowing students to explore concepts like chemical reactions or complex experiments where multiple variables can be precisely controlled in a safe and controlled environment. This capability can significantly enhance students' understanding of scientific principles while minimizing risks associated with traditional experimentation.

VR in Teacher Preparation: Developing 21st-Century Science Educators

Incorporating VR into preservice science teacher education holds great potential, not only as a tool for teaching students but also as a means to enhance the preparation of future educators. Teachers' willingness to adopt new technologies is often a key factor in the successful diffusion of innovations in education (Khukalenko et al., 2022), which can play a crucial role in bridging the gap between theoretical knowledge and hands-on experience. The lead author, a facilitator at VRA, provided preservice teachers with opportunities to observe various middle-grade VR classroom sessions. These preservice teachers join as avatars and experience the dynamics of a typical 5E lesson, where they listen in on student groups working through science concepts and then watch the teacher lead a class discussion during the explanation phase. Research supports the value of such experiences, with studies like Van der Want and Visscher (2024) noting that VR environments allow preservice teachers to practice professional competence in diverse, safe settings, boosting their teaching skills and self-efficacy. Importantly, many preservice teachers, including those initially skeptical, emerge with a positive outlook after engagement with VR, citing increased motivation and engagement (Van der Want & Visscher, 2024).

The positive experiences of these preservice teachers echo the findings of Domingo and Bradley (2018), who reported that most participants in their study had a favorable experience with VR as part of their coursework. Interestingly, half of the initially pessimistic participants shifted to a positive perception by the end of the study, suggesting that resistance to VR adoption may stem more from unfamiliarity than from inherent shortcomings of the technology. The previous research on changing perspectives of VR in education after experiences in VR aligns with the work of Kızılay et al. (2024), who emphasize that early familiarity with VR in teacher education programs is key to fostering an openness to innovative tools in the classroom. Such engagement with VR helps preservice teachers build confidence in using technology and enhances critical thinking and problem-solving skills—core components of modern science education (Paxinou et al., 2022).

The instructor's observations of preservice teachers at VRA further illustrate VR's capacity to support teacher preparation. As preservice teachers watch students engage with complex scientific concepts in the immersive VR environment, they see firsthand how the technology can simulate experiments and phenomena that are difficult or unsafe to demonstrate in traditional classrooms. A safer and cost-effective avenue for experimentation allows future educators to develop a broader toolkit of instructional strategies that engage students and deepen their understanding of STEM subjects. Moreover, VR facilitates the integration of technological, pedagogical, and content knowledge (TPACK) in lesson planning and reflection (Ga, Cha, & Yoon, 2024), ensuring that preservice teachers can both confidently use and meaningfully integrate the technology, but also be capable of incorporating it effectively into their teaching practice. The success of these VR sessions highlights the importance of incorporating VR into teacher education, ensuring that preservice teachers are well-prepared to adopt and integrate STEM technologies in their classrooms.

Conclusion

As future educators, preservice teachers need to be familiar with emerging technologies like VR to be aware of the possibilities regarding potential impacts on instruction. While there is currently only one VR school, an increasing number of schools are incorporating VR technology into science lessons to provide immersive experiences, such as exploring different species' habitats and the molecular world. An estimated 15% of U.S. schools are estimated to have access to virtual reality for science education (Herold, 2018). Although not all preservice teachers will have direct access to VR technology, finding opportunities to observe VR science classes is critical for their professional development.

In the context of Roger's (2003) DOI theory, the experiences these preservice science teachers have had place them somewhere in the early adopter or early majority groups, enabling them to see the advantages of VR in student learning and engagement. In addition, participating in VR lesson observations allows them to more easily assess VR's instructional value and consider how it can be effectively integrated into conventional teaching methods. While direct evidence of the PSTs' ability to integrate VR is beyond the scope of this investigation, insights inferred from their participation in VR lesson observations suggest an increasing awareness of both the potential benefits and challenges of using VR in science education. As they consider integrating VR into their future classes, these science teachers may subsequently influence colleagues and advance the infusion of VR technology in teaching at their schools. Their virtual reality experiences may help expand VR adoption in science education beyond individual innovators, reaching a broader professional network and promoting ongoing integration of this innovative technology.

Providing preservice teachers with unique opportunities to observe VR classroom lessons allows them to witness firsthand how this technology engages students and enhances conceptual understanding. VR has clear advantages, including the ability to create immersive, interactive environments that foster deeper learning and student engagement. However, its disadvantages, such as limited access due to cost and technical challenges, highlight the importance of creative approaches, such as online demonstrations or collaborations with schools utilizing VR. By observing and reflecting on VR science instruction, preservice teachers can better understand its pedagogical potential and consider how to adapt such innovative tools within their teaching practices. Ultimately, immersive technologies like VR are not only tools of novelty but strategic assets for equitable, engaging science instruction, especially when thoughtfully integrated into teacher education.

As VR technology continues to evolve, further research is needed on the long-term impacts of VR instruction so that educators can better understand the full scope of VR. Certain studies, such as Vesisenaho et al. (2019), suggest the importance of teachers being aware of students' prior knowledge, self-regulated learning strategies, and engaging with relevant content to maximize the benefits of VR for students. Moreover, involvement in VR-based learning must be explored, especially the influence of preservice teachers' comfort level with the use of technology and the change in engagement with increased VR use (Huang et al., 2021). The development of interactive AI-driven learning environments, such as Engage XR's School of AI, further underlines the need to familiarize preservice teachers with emerging VR technologies. Lastly, longitudinal studies are needed with preservice teachers to verify whether they enter the classroom better prepared because of VR-based preparation and if they will use VR in their teaching. Understanding and developing the role of VR in science education requires a comprehensive understanding of its dynamics and practical implementation.

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