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INNOVATIONS IN PHYSICS TEACHING THROUGH IMMERSIVE TECHNOLOGIES: AN ANALYSIS OF SCIENTIFIC PRODUCTION

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Abstract: This study presents a structured literature review of recent academic research on the use of immersive technologies in physics education. Publications from 2019 to 2024 were collected from Google Scholar, SciELO, and the CAPES Periodicals Portal using predefined search strategies. The review analyzes the pedagogical applications of virtual reality (VR), augmented reality (AR), and other immersive environments. The findings indicate that these technologies support student learning by enabling interactive visualization and manipulation of physical phenomena, particularly in areas such as mechanics, electromagnetism, and astronomy. Reported benefits include increased engagement, improved conceptual understanding, and enhanced scientific reasoning. However, challenges remain, including infrastructure limitations, teacher training needs, and curriculum integration. The results suggest that digital environments are effective when used as complementary tools within well-structured pedagogical approaches.

Key words: Education strategies. Physical sciences. Virtual and Augmented environments.

1. Introduction

Physics education presents persistent challenges related to the abstract nature of its concepts, mathematical complexity, and the difficulty students face in visualizing physical phenomena across different scales (Moreira, 2021). These factors often hinder meaningful learning and limit students' conceptual understanding.

In response to these challenges, educators have increasingly sought innovative methodologies capable of making physics instruction more accessible, engaging, and pedagogically relevant. In recent years, advances in digital technologies—particularly immersive tools such as virtual reality (VR), augmented reality (AR), and three-dimensional virtual environments—have opened new possibilities for education. These technologies enable students to interact with simulated scenarios, manipulate virtual objects, and explore representations of physical phenomena that are often difficult to observe in traditional classroom settings (Tori & Hounsell, 2020).

The integration of immersive technologies into physics teaching holds considerable potential, as it allows students to engage more directly with abstract concepts, fostering intuitive understanding through interaction and visualization. However, despite these advantages, important challenges remain, including limitations in infrastructure, high implementation costs, the need for teacher training, and difficulties in aligning such technologies with existing curricula.

From a theoretical perspective, the use of digital environments in education can be supported by different learning frameworks. Constructivist theory emphasizes that knowledge is actively constructed through interaction with the environment, which aligns with the interactive nature of VR and AR experiences. Experiential learning theory highlights learning through direct experience and reflection, while multimedia learning theory supports the integration of visual and interactive elements

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to enhance cognitive processing. These perspectives help explain why immersive technologies may contribute to improved learning outcomes, rather than only describing their effects.

Given the growing body of research in this area, it is essential to critically examine how immersive technologies have been applied in physics education and what impacts they have produced. In this context, the following research questions guide this study: To what extent do digital environments enhance the understanding of physical concepts? Which areas of physics benefit most from these approaches? What are the main challenges associated with their implementation?

This article aims to address these questions by conducting a literature review of studies published within the past five years on the use of immersive technologies in physics education. The objective is to analyze current scientific production in the field, identifying trends, contributions, challenges, and opportunities for future research and pedagogical practice.

2. Methodology

The methodological approach employed in this study involves a literature review focusing on the use of virtual reality (VR), augmented reality (AR), and immersive environments as pedagogical resources in physics education. As noted by Dane (1990), a literature review helps delineate the theoretical and empirical scope of a study from a scientific perspective. The author emphasizes the importance of identifying key elements such as major themes, prominent scholars, specific terminologies, scholarly journals, and primary data sources. Complementing this view, Webster and Watson (2002) consider literature reviews a foundational component of any scientific investigation. Gil (2007) describes this type of research as one grounded in existing academic production, including books, peer-reviewed articles, and dissertations. According to the same author, literature reviews are exploratory by nature, enabling closer engagement with the subject matter, refinement of concepts, and the emergence of new insights.

This study adopts a systematized literature review approach, inspired by PRISMA guidelines, with the aim of identifying, selecting, and analyzing relevant studies on immersive technologies in physics education. In addition to the selection process, a qualitative analytical procedure was employed, based on thematic categorization of the selected studies, allowing the identification of recurring pedagogical contributions, technological applications, and implementation challenges.The search process was conducted in three major academic databases: Google Scholar, SciELO, and the CAPES Periodicals Portal, covering literature published between 2019 and 2024. The search was performed using specific search strings, combining terms related to digital environments and physics education. The main search strings employed were: ("virtual reality" OR "augmented reality" OR "immersive technologies") AND ("physics education" OR "physics education" OR "physics learning"). Boolean operators (AND, OR) were applied to refine the results and ensure comprehensive coverage of the relevant literature.

The inclusion criteria were defined as follows: (i) studies published between 2019 and 2024; (ii) peer-reviewed articles, theses, or dissertations; (iii) studies that explicitly address the application of immersive technologies in physics teaching; and (iv) works that present empirical or theoretical contributions to teaching and learning processes.

The exclusion criteria included: (i) studies not focused on physics teaching; (ii) publications not available in full text; (iii) duplicate records; and (iv) studies that mentioned immersive technologies without pedagogical application. The initial search resulted in 68 records. After removing duplicates and screening titles and abstracts, 25 studies were selected for full reading. Of these, thirteen studies met all inclusion criteria and were included in the final analysis.

The study selection process followed the guidelines of a flowchart, similar to that recommended by the PRISMA protocol, to ensure transparency and reproducibility. Initially, 68 records were identified in the databases. After removing 5 duplicates, 63 records were screened by title and abstract. Of these, 38 were excluded for not meeting the thematic relevance criteria. The remaining 25 studies were evaluated in full text, resulting in the exclusion of 12 for not meeting the specific inclusion criteria (e.g., lack of pedagogical focus, unavailability of full text). Thus, 13 studies were finally included in the qualitative synthesis.

The final set of studies was analyzed using qualitative content analysis procedures, focusing on identifying recurring themes related to pedagogical benefits, technological affordances, and implementation barriers. The analysis followed a process of categorization and comparison across studies, enabling the synthesis of converging and diverging findings.

3. Results and Discussion

As outlined in the methodology section, thirteen studies were examined to explore the role of immersive technologies in the teaching of physical concepts. This section presents a synthesis of those findings, outlining the pedagogical potential, implementation challenges, and specific tools addressed in the reviewed literature.

Roberto et al. (2024) investigate the use of AR as a transformative strategy in physics instruction, particularly in leveraging the increasing availability of smartphones in educational settings. Their findings demonstrate that AR significantly enhances student interaction and comprehension, particularly for abstract topics like optics. The project not only yielded a functional application and multiple virtual objects but also equipped students with 3D modeling skills.

Additionally, the integration of AR into classrooms was facilitated by the development of printed marker booklets, demonstrating that sophisticated equipment is not always necessary. The positive outcomes suggest that AR has the potential to be extended to other subjects, reinforcing the foundations of technology-enhanced pedagogy.

In a similar vein, Araújo, Oliveira, and Silva (2022) conducted a systematic review focusing on postgraduate capstone projects involving AR in Brazilian physics education. Their analysis revealed that most initiatives aimed to create teaching aids rooted in cognitive learning theories. Six studies were reviewed, emphasizing the practical implementation of AR-based materials and their alignment with student learning processes.

Students reported positive experiences with AR, noting both its pedagogical and technical benefits. A publication gap between 2012 and 2014 was identified, followed by a steady increase in output after 2015, coinciding with the widespread adoption of mobile AR technology.

The reviewed works also underscored the relevance of aligning learning theories with AR practices in the classroom. The authors caution, however, that AR should be considered a supportive tool rather than a standalone solution to educational challenges.

Further exploring AR's role in physics education, Diniz and Pastorio (2023) performed a systematic literature review on the development and use of three-dimensional virtual worlds (3DVWs). Their analysis covered 16 studies sourced from academic journals and Brazil's Digital Library of Theses and Dissertations. Topics spanned various physics domains, with a concentration on mechanics concepts such as collisions, angular momentum, and horizontal projectile motion.

These immersive environments fostered meaningful learning by simulating real-world phenomena and simplifying abstract ideas. Notably, electromagnetism and optics were less frequently addressed. Research methodologies involved the design of educational games, simulation tools, and instructional sequences using platforms like Unity 3D, Second Life, and AR applications. Most evaluations employed qualitative methods in K-12 classrooms, using surveys and participant reflections.

Suzart and Ferreira (2023) describe the creation and assessment of an AR-based educational tool called *Circuits*, designed for high school instruction in electric circuits. Initial findings indicated that many students struggled with physics, especially electrical topics. The tool, developed using the Metaverse Studio platform, covered elements of electric circuits, circuit types, and resistor configurations.

Four physics teachers assessed the AR tool through questionnaires addressing its interactivity, accessibility, and content clarity. The overall feedback was positive, with educators highlighting its capacity to engage learners and promote dynamic classroom experiences. Nonetheless, technical challenges were noted, such as video playback issues and sensor inconsistencies. One teacher also recommended refining some concept explanations.

In another study, Ribeiro, Caldas, and Macedo (2021) evaluated an AR tool designed to facilitate understanding of magnetic field lines around cylindrical magnets and straight conductors. Conducted with high school seniors, the research compared students' conceptual models before and after the AR intervention. The results showed enhanced spatial reasoning and a clearer grasp of three-dimensional magnetic fields.

Survey responses revealed that 83% of students felt AR improved their understanding of the magnetic field concept, while 85% expressed interest in using AR for other physics topics. Though technological adaptation posed some challenges, the overall assessment affirmed the tool's pedagogical value.

Based on the reviewed literature, AR emerges as a promising support for teaching physics. Teachers are encouraged to leverage students' smartphones to access AR resources, provided that adequate guidance and monitoring are in place, as noted by Santana, Ferreira, and Duarte (2023).

Bela (2022) investigated AR's application in astronomy education for seventh-grade students. The goal was to design and test a prototype that would assist in visualizing complex astronomical phenomena. Using a design-based research methodology, the study assessed both pedagogical efficacy and usability in real classroom settings.

Results indicated that AR use significantly enhanced students' conceptual understanding, interaction, and engagement. The findings revealed a strong correlation between AR integration and students' ability to assimilate content, reinforcing its potential as a valuable tool in science education.

Shifting focus to VR applications in physics education, Tito and Moraes (2023) evaluated the effects of a VR game, *ORUN-VR*, on students' understanding of kinematics. Experimental groups using the game achieved learning gains averaging 52% over control groups, with statistically significant improvements verified through pre- and post-test comparisons.

Ferreira et al. (2021) explored the impact of VR on teacher engagement during collaborative simulations involving projectile motion, conducted on the Sandbox platform. Students participated in real-time discussions via chat, exchanging ideas and forming arguments. The authors concluded that VR environments not only aid content understanding but also foster critical reasoning and collaborative learning skills in teacher education contexts.

Figure 1. Sandbox Software

The authors conclude that the use of virtual learning environments can serve as a powerful tool in teacher training, as it supports not only the acquisition of subject-specific knowledge but also the development of argumentative skills essential in an increasingly digital educational context. Student feedback suggests that VR facilitates engagement with contemporary educational demands, expanding the horizons for both teaching and learning.

The global scope of this topic is evident when examining international contributions. Lakka, Zafeiropoulos, and Leisos (2023) present a case study in a physics laboratory utilizing VR equipment. They highlight the advantages of the "Virtual Reality Laboratory" (VRL) methodology, especially for distance education programs where geographical and scheduling constraints are common. Aligning VRL sessions closely with theoretical courses proved instrumental in achieving improved learning outcomes.

The authors emphasize the VRL's flexibility and the autonomy it fosters, noting its substantial value in the context of remote laboratory instruction. They propose enhancements to the VRL model, including features such as instructional guidance, hypothesis generation, and self-assessment tools, aiming to further empower students to conduct independent experiments.

Through a bibliometric analysis, Prahani et al. (2022) explore trends in the integration of AR and VR in physics education from 2002 to 2021. The study identifies key contributors, journals, and research domains related to immersive technology in education. Findings emphasize the growing pedagogical relevance of AR and VR, their role in enhancing conceptual understanding, and their prominence in publications from countries such as the United States, China, and Germany, especially within computer science and engineering disciplines. The authors conclude that AR and VR have become prominent themes in 21st-century physics education research.

Yin et al. (2021) offer a comprehensive review of recent advances in AR and VR display technologies. Their study tracks the evolution of these systems and outlines the design requirements necessary to ensure visual comfort and usability. The analysis covers various display architectures, including optical properties, 3D imaging capabilities, field of view, resolution, and illumination. The authors also discuss current challenges in achieving portability and user comfort, highlighting innovations such as folded optics and polarization techniques aimed at reducing device size and weight.

4. Final Considerations

The findings of this review provide answers to the research questions proposed in this study. Regarding the extent to which immersive technologies enhance the understanding of physical concepts, the analyzed studies consistently indicate improvements in visualization, engagement, and conceptual comprehension. Concerning the areas of physics that benefit most, mechanics, electromagnetism, and astronomy emerged as the most frequently addressed domains. Finally, the main challenges identified include infrastructure limitations, teacher training requirements, and difficulties related to curriculum integration.

Nevertheless, challenges persist—namely, the high cost of implementation, the pressing need for teacher training, and the difficulty of integrating these technologies into existing curricula. Addressing these barriers is essential to unlocking the full potential of immersive tools in educational practice.

Educators and institutions must draw from the reviewed evidence to create environments conducive to adopting such innovations. The intersection of immersive technology and physics instruction presents a clear opportunity for pedagogical advancement, as highlighted throughout the studies examined.

Despite its contributions, this study presents some limitations. The review was restricted to three databases and a specific time frame (2019–2024), which may have excluded relevant studies published in other contexts. Additionally, the qualitative nature of the analysis does not allow for generalization of findings, reinforcing the need for further empirical investigations.

Thus, the research affirms that the integration of digital environments into physics education should be accompanied by critical reflection and supportive educational policies that ensure ongoing teacher development. Continued investigation and refinement of instructional strategies will be necessary not only to overcome existing limitations but also to broaden access and relevance for future generations of learners.

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