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LITERATURE REVIEW ARTICLE

Virtual Reality in STEM-Physics Education: A Systematic Review of Impacts on Critical Thinking and Collaboration

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Abstract

The main aim of this work is to review the literature on the implementation of virtual reality (VR) technology in physics education within STEM (science, technology, engineering, and mathematics). The main objectives are improving students' capacity for critical thinking and teamwork. Physics is abstract, and conventional teaching strategies are dull; hence, it is sometimes a challenging subject. Virtual reality (VR) presents a more interesting learning experience through interactive simulations in a three-dimensional environment, thereby enhancing students' comprehension. Using the PRISMA approach, we chose 100 papers for this study; subsequently, we cut the total to 20 relevant ones for more investigation. According to the study's findings, VR might help one develop critical and cooperative thinking abilities as well as grasp difficult physics topics. The lack of teacher training and the expensive cost of the devices aggravate the challenges in implementing this technology. Although virtual reality (VR) is a very successful creative tool for enhancing the efficacy and involvement of physics education, its deployment in classroom environments needs more help, according to the study.

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INTRODUCTION

Over the past decades, technological advancement has profoundly transformed various domains of human activity, including education. Among emerging technologies, virtual reality (VR) has garnered increasing attention for its potential to revolutionize instructional practices. By enabling immersive three-dimensional experiences, VR bridges the gap between abstract scientific concepts and students' cognitive frameworks. In subjects like physics—which demand the visualization of complex, often intangible phenomena—VR can enhance learners' comprehension through interactive experimentation and real-time simulations.

Moreover, the STEM (science, technology, engineering, and mathematics) education system fits the application of virtual reality in physics instruction (Mawarni, 2024). STEM education emphasizes including these four disciplines in teaching and learning strategies to equip students or teenagers to confront the more complicated and uncertain challenges of the fast-changing future job market. Thus, we must enhance students' critical thinking and collaborative abilities, which are crucial skills in the Industry 4.0 era (Tene et al., 2024).

Several research have demonstrated that teaching with virtual reality might help students learn better. For example, Merchant and his coauthors found that adopting virtual reality (VR) in scientific classes could help students understand concepts better and want to learn more (Merchant et al., 2014). Parong and Mayer (2018) claim that virtual reality (VR) could assist students understand difficult physics concepts while also getting better at thinking critically. Some of the reasons why schools don't use VR more are that it costs a lot, instructors need to be taught, and there isn't enough support for it (Parong & Mayer, 2018; Poltak Gultom et al., 2024).

Past studies have shown that virtual reality can help students focus, get interested, and learn more about physics. Virtual reality can also aid kids to acquire two essential 21st-century skills: critical thinking and team collaboration (Budi et al., 2021). This post is largely on how virtual reality can help STEM-based physics students improve their teamwork and critical thinking skills. This article talks about how digital tools, like virtual reality, could help students learn about science by encouraging them to research, evaluate, and work together to solve both theoretical and real-world problems. The purpose of this study is to look at all the ways VR is used in physics classrooms that are based on STEM to help students get better at working together and thinking critically (Papanastasiou et al., 2019). This study will look at all the good and bad things about utilizing virtual reality (VR) to teach physics, as well as possible remedies (Alfarid et al., 2022). This study's conclusions can help teachers make the most of virtual reality (VR) in their physics classes. These findings could also help education policymakers figure out how to employ VR to improve physics teaching in Indonesia (Alif & Hariyono, 2020).

While emerging studies acknowledge the potency of VR in driving student engagement, existing systematic literature reviews exhibit a critical dual omission. First, prior meta-analyses frequently evaluate VR as a generalized visualization tool, rarely dissecting its specific intersection with STEM-driven physics or isolating its simultaneous effects on cognitive (critical thinking) and social (peer collaboration) 21st-century dimensions. Second, the current literature tends to present descriptive summaries rather than analyzing pedagogical efficacy through structured frameworks. This global pedagogical gap leaves educators without a systematic blueprint. Consequently, this study addresses these limitations by evaluating how immersive environments transform abstract physics concepts globally, while providing actionable insights tailored to developing educational landscapes, including Indonesia.

METHOD

We used the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) technique to undertake a structured review of the research that already exists on how virtual reality could help students in physics enhance their critical thinking and collaborative skills. A systematic literature review combined with PRISMA gives a clear and easy-to-understand way to explore, and it works very well in schools, especially for learning physics (Page et al., 2021) . This technique works because it lets you collect results and interpretations based on real evidence by discovering each abstract and carefully sorting publications based on the study subject.

The approach utilized is a systematic literature review employing the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework. The PRISMA framework provides a systematic and transparent approach for conducting literature reviews applicable across various academic disciplines, including physics education. PRISMA assists researchers in ensuring that their literature search and reporting methods are conducted accurately and can be replicated. This enhances the reliability and quality of their research findings (Rethlefsen et al., 2021). This strategy was selected as it enables researchers to identify and categorize significant papers, ensuring the inclusion of only pertinent research (Matos et al., 2023).

Data Source

We got the databases for our investigation via Google Scholar and Publish or Perish. While emerging studies acknowledge the potency of VR in driving student engagement, existing systematic literature reviews exhibit a critical dual omission. First, prior meta-analyses frequently evaluate VR as a generalized visualization tool, rarely dissecting its specific intersection with STEM-driven physics or isolating its simultaneous effects on cognitive (critical thinking) and social (peer collaboration) 21st-century dimensions. Second, the current literature tends to present descriptive summaries rather than analyzing pedagogical efficacy through structured frameworks. This global pedagogical gap leaves educators without a systematic blueprint. Consequently, this study addresses these limitations by evaluating how immersive environments transform abstract physics concepts globally, while providing actionable insights tailored to developing educational landscapes, including Indonesia. The papers that were looked at for analysis focused on the last 10 years, from 2018 to 2025 (Wiyanto et al., 2020) . The article search process has four steps: keyword identification of articles, filtering according inclusion-exclusion criteria, eligibility verification, and article selection satisfying all analysis requirements (Mohamed et al., 2020).

Selection Criteria

The criteria for articles to be included in this literature review can be found in table 1:

Table 1. Inclusion and Exclusion Criteria

Information	Inclusion	Exception
Document Type	International articles or SINTA-accredited articles	In Addition to Articles international or SINTA-accredited articles
Method	Literature Review, qualitative and R&D	In addition to Literature Review, qualitative and R&D
Accessibility	Articles can be downloaded	Articles that cannot be downloaded
Keywords	virtual reality; STEM; critical thinking skills; student collaboration ; physics learning media	Besides keywords
Aspects measured	Critical thinking, collaboration, student motivation, learning outcomes, conceptual understanding	In addition to critical thinking, collaboration, student motivation, learning outcomes, conceptual understanding
Language	English or Indonesian	Besides English and Indonesian
Publication Year	2018-2024	Apart from 2018-2024

The article selection process is carried out using the inclusion and exclusion criteria explained in table 1 to make it easier to select and filter the articles to be taken and their suitability to the theme and objectives of the research. The article selection criteria are determined based on several important aspects, namely, first, the type of document used must be a national (Sinta) or international (Scopus) article, while articles other than these two categories will be excluded. From the methodology, only articles that use the literature review method,litative research, and research and development will be taken; otherwise, they will not be taken. The accessibility of the article is also considered; only articles that can be downloaded can be analyzed, but if the relevant article cannot be downloaded but its abstract has clearly stated its objectives and results, it can be considered. Furthermore, the article being searched for must contain the keywords that have been determined, namely, virtual reality, STEM, critical thinking skills, student collaboration , and physics learning media.

In terms of language, only articles written in Indonesian or English can be analyzed, and publications from 2018 to 2025.

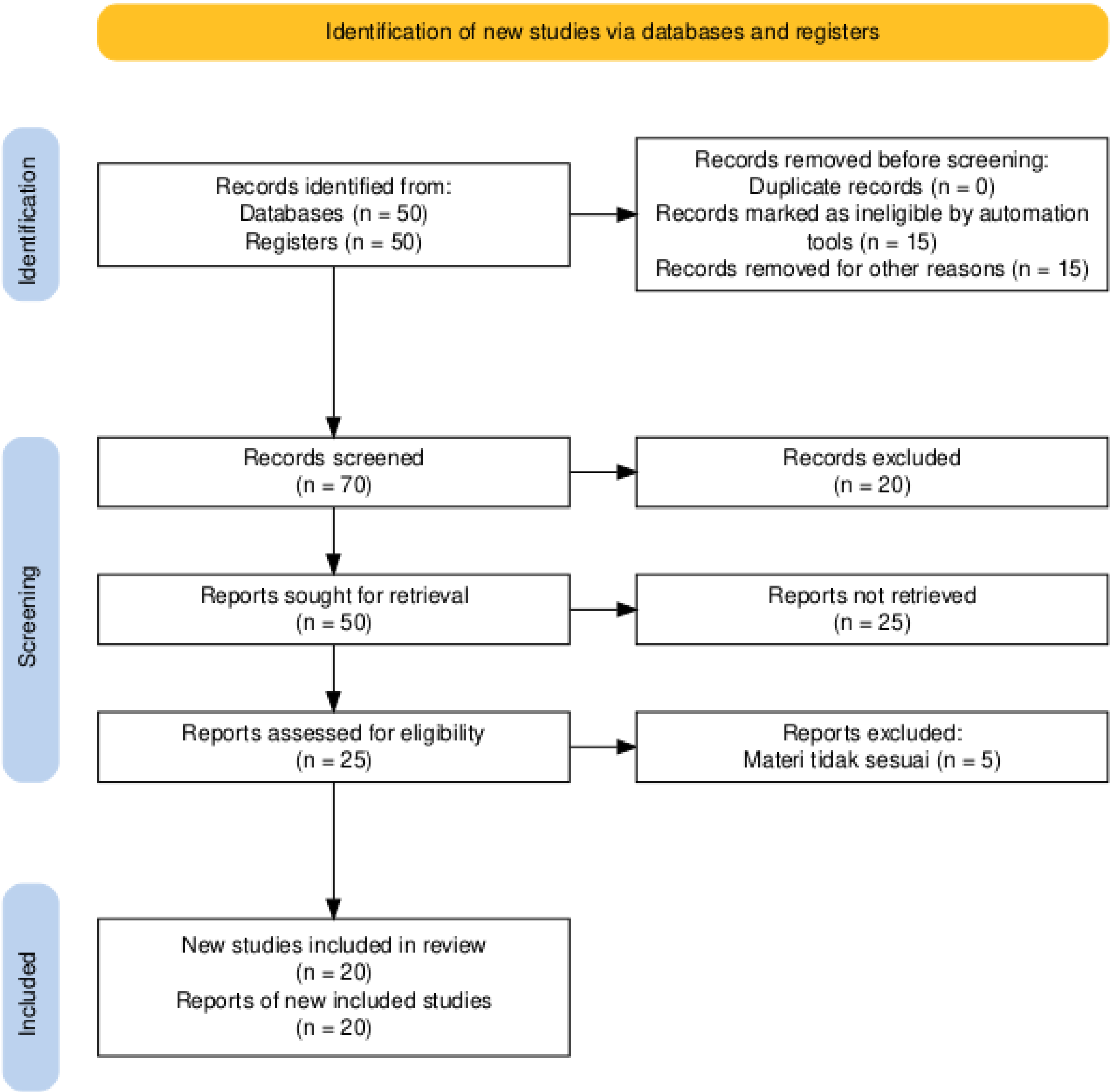

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) flowchart

Research Design and Procedurs

The article search began by identifying 100 national (Sinta) and international (Scopus) articles from two sources, namely Google Scholar and Publish or Perish. 15 articles were automatically deleted because they did not meet the requirements, namely the method used did not match the inclusion criteria, and 15 more did not match the keywords, leaving 70 articles. At the screening stage, 20 articles were removed because they were irrelevant, namely, they did not match the research objectives and aspects measured; then 50 articles remained. However, 25 of them could not be accessed/downloaded. Out of 25 articles, there were 5 articles that did not match the material. At the included stage, 20 articles were found that were eligible and met all the criteria; then, after that, this article will be further analyzed starting from the abstract, objectives, and results of the study

RESULT AND DISCUSSION

Articles that have passed the stages will then be analyzed and studied further from the abstract to the conclusion.

Table 2. Article Analysis Results

No	Author's name	Method	Publication Year	Aspects measured	Research result
1	Durukan, et all,.	Literature study	2020	The use of Virtual Reality and its effectiveness	The use of virtual reality (VR) technology in science education has significant potential to enhance student conceptual understanding and engagement.
2	Sumardani et al.	Research and Development (R&D)	2019	Conceptual understanding, student collaboration and learning effectiveness	The use of VR applications in physics learning has a positive impact.
3	Harnisa	Qualitative descriptive	2023	Student learning outcomes and collaboration	Students' learning outcomes in understanding physics formulas and equations still need to

No	Author's name	Method	Publication Year	Aspects measured	Research result
					be improved.
4	Atika et al.,	Research and Development (R&D)	2023	Effectiveness of learning, critical thinking and student collaboration.	The average pretest score of students before using the media was 41.12, while the average post-test score after implementing the media reached 74.78, indicating a significant increase.
5	Prillyanti , et al.,	Systematic approach	2023	Learning outcomes, student responses and critical thinking.	The N-gain obtained was in the moderate category, namely 0.67, which indicates a significant increase.
6	Munawaroh et al.,	Experimental research	2023	Critical thinking skills	The average score of students' critical thinking skills was 58.38, which is included in the moderate category.
7	Firdaus et al.,	Quantitative approach	2024	Understanding concepts and critical thinking	The increase in conceptual understanding in the experimental class reached 63.42% with an N-gain of 7.4, while the control class only reached 8.52% .
8	Sukmawati et al.,	Development with 4D model design	2022	Student learning interest and collaboration	This media is suitable for use in learning, with ease for students in understanding the material and increasing interest in learning.

No	Author's name	Method	Publication Year	Aspects measured	Research result
9	Fradika et al.,	Research and Development (R&D)	2018	Effectiveness, understanding of material, and critical thinking	improving the quality of learning and student engagement through VR-based multimedia technology.
10	Bakar et all.,	quasi-experimental method	2019	Critical thinking and scientific attitude	The use of VR helps make learning more interesting, interactive and effective.
11	Bambang et al.,	Literature study	2022	Effectiveness, Improving Critical Thinking Skills	Students showed improvements in their critical thinking skills and collaborated in groups to complete tasks involving the use of VR applications.
12	Abdullah et al.,	Experiments with virtual reality technology	2019	Group work and independent learning skills	VR improves group work skills and independent learning
13	Allcoat, et all.,	Experiments with VR in the learning process	2018	Performance, emotion and engagement	VR significantly impacts performance, emotions and engagement
14	Enitan et al.,	Literature study and descriptive analysis	2024	Improving educational outcomes across disciplines	VR improves educational outcomes across disciplines
15	Jensen, L et al.,	Literature review	2018	Use of VR HMDs in education	VR with HMD is very effective in education
16	Rojas Sanchez et al.,.	Literature review and bibliometric	2023	VR literature and education	The increasing use of VR in education and research trends

No	Author's name	Method	Publication Year	Aspects measured	Research result
		analysis			
17	Tene et all.,	Systematic review	2024	Integration of VR technology with STEM education	VR integration strengthens STEM education
18	van der Meer et al.,	Systematic literature review	2023	Collaborative learning through VR	VR increases the effectiveness of collaborative learning
19	Zhang, W et all.,	Systematic literature review	2021	VR/AR theory and practice in science education	VR and AR are having a huge impact on K-12 education
20	Cook, M et all.,	Case studies and interviews	2019	VR challenges and strategies in education	Identify the main challenges of VR in education and strategies to overcome them

Background and Problems

The predominant challenge encountered within the realm of science education pertains to the insufficient application of Virtual Reality (VR) technology. Despite the substantial promise that VR holds for augmenting the comprehension of scientific principles, its implementation within educational settings remains markedly constrained. A principal factor contributing to this limitation is the scarcity of resources and comprehensive investigations regarding the efficacy of VR in science education, which engenders a reluctance among educators and institutions to assimilate this technology into the academic curriculum (Durukan et al., 2020; Enitan et al., 2024; Sukmawati et al., 2022). In the context of Indonesia, numerous educational institutions exhibit considerable hesitance in adopting technology-mediated learning tools such as VR, thereby adversely influencing students' engagement and interest in learning, particularly in disciplines like physics that are perceived as challenging (Fradika & Surjono, 2018). Learners frequently encounter difficulties in grasping abstract concepts in physics, such as mathematical formulas or equations that pose significant cognitive challenges, especially when pedagogical approaches remain entrenched in traditional methodologies, such as lectures that fail to incorporate pertinent real-world examples (Allcoat & von Mühlenen, 2018; Harnisa, 2023) .

Nevertheless, empirical evidence indicates that when VR is effectively integrated, it has the potential to significantly improve educational outcomes, encompassing both conceptual understanding and critical analytical competencies. The principal obstacle resides in the inadequacy of sufficient infrastructural support and rigorous research concerning the implications of VR, which obstructs the seamless incorporation of this technology into the academic syllabus (Cook et al., 2019; Rojas-Sánchez et al., 2023). Consequently, it becomes imperative to investigate the efficacy of VR across diverse educational frameworks, particularly its capacity to bolster student engagement and motivation within Indonesian educational institutions, especially in subjects perceived as demanding, such as physics.

Analysis and Problem Solving

Several studies indicate that virtual reality (VR) improves conceptual understanding; however, the lack of resources and in-depth research on its effectiveness in science education causes teachers and institutions to hesitate in integrating this technology into the curriculum (Jensen & Konradsen, 2018). The extant body of literature concerning the application of virtual reality (VR) within the educational domain reveals heterogeneous outcomes, with certain investigations underscoring substantial advancements in student learning achievements, whilst others suggest that its efficacy is considerably contingent upon contextual variables. Numerous studies illustrate that VR has the capacity to augment conceptual comprehension by offering interactive and immersive experiences that are challenging to replicate through conventional pedagogical approaches (Sumardani et al., 2019; van der Meer et al., 2023); the use of VR-based multimedia can improve the quality of learning to be more interesting, and students are more motivated (Fradika & Surjono, 2018). Conceptual understanding in the experimental class increased significantly when compared to the control class (Firdaus, 2024).

Nonetheless, these findings are not invariably uniform, and various studies concede that the effectiveness of VR may hinge upon elements such as sample size, research methodology, and the specific context of its implementation. For instance, despite a plethora of studies indicating that VR can improve critical thinking and problem-solving abilities (Bakar et al., 2019; Zhang & Wang, 2021), there exist several studies characterized by limited sample sizes or constrained research designs, thereby prompting inquiries regarding the dependability and generalizability of the findings. After using VR, students' test scores increased from 41.12 to 74.78 (Atika et al., 2024).there was an increase in N-gain of 0.67, which shows the effectiveness of VR in improving critical thinking skills (Prillyanti & Anggaryani, 2023),the critical thinking ability score, which was initially in the low category, increased to the medium category with a value of 58.38 (Munawaroh et al., 2021) and students who have learned to use VR show significant progress in critical thinking skills and group cooperation between students (Abdullah et al., 2019; Bambang et al., 2022). Consequently, there is an imperative for further research that encompasses larger sample sizes and a broader range of contexts to accurately evaluate the genuine potential of VR. A primary challenge identified within this research domain is the absence of a coherent analytical framework. Numerous studies are articulated in a linear and descriptive manner without categorizing the outcomes utilizing a specified framework, such as TPACK (Technological Pedagogical Content Knowledge) or 21st Century Skills. The incorporation of such analytical frameworks would facilitate the systematic organization of findings and yield clearer insights into the contributions of VR to various dimensions of learning, including conceptual understanding, collaborative engagement, and critical thinking competencies.

Advantages of Virtual Reality

The application of virtual reality (VR) in the realm of education presents numerous advantages, particularly in augmenting student engagement and enhancing their critical thinking capabilities. Educational programs that synergize VR with deductive reasoning methodologies can facilitate the development of both critical and creative cognitive skills among students. Through the integration of VR technologies, students are afforded the opportunity to engage with complex scientific concepts within an immersive and interactive environment, thereby potentially improving their comprehension and intrinsic motivation (Fradika & Surjono, 2018; van der Meer et al., 2023).

Moreover, immersive learning environments grounded in VR have been empirically demonstrated to bolster collaborative and problem-solving abilities among learners. Collaborative efforts within a virtual framework allow students to cultivate essential teamwork skills that are paramount in the context of 21st-century competencies. Empirical research indicates that VR can significantly deepen students' understanding of intricate scientific principles, simultaneously fostering their capacity for critical and analytical thinking (Bambang et al., 2022; Abdullah et al., 2019). Nonetheless, the efficacy of VR in nurturing critical thinking and collaborative skills is likely contingent upon the specific educational context, including variables such as educational level (for instance, high school versus university) and geographical location (for example, Asia compared to Europe).

Technological Pedagogical Content Knowledge (TPACK) Synthesis

Evaluating the 20 selected articles through the lens of the TPACK framework reveals how VR functions not merely as an isolated technological add-on, but as a core catalyst at the intersection of Content Knowledge (Physics) and Pedagogical Knowledge (STEM-driven collaborative learning). From the Technological Content Knowledge (TCK) perspective, VR transforms abstract, intangible physical phenomena, such as gravitational fields, Kepler’s Laws, or special relativity into manipulable three-dimensional structures. This structural visualization underpins the documented cognitive shifts; for instance, resolving misconceptions in abstract concepts allowed students' critical thinking scores to rise significantly into a solid moderate category (mean score of 58.38; N-gain of 0.67).

Simultaneously, the Technological Pedagogical Knowledge (TPK) dimension illuminates the mechanism behind student collaboration, which has previously been under-analyzed in a statistical manner. The review demonstrates that when VR is deployed within problem-based or project-based STEM narratives, it creates shared cognitive environments. Unlike traditional environments where students work in isolation, immersive VR systems force learners to negotiate spatial orientation, delegate technical and conceptual roles, and co-evaluate real-time simulation variables to solve complex physical equations. This interactive interdependence directly fosters group work proficiency and independent learning skills, providing a empirical baseline that balances social collaboration with individual cognitive gains.

Statistical Summary and Framework

A quantitative synthesis of the studies reviewed will prove instrumental in elucidating the ramifications of VR on educational outcomes. For instance, among the 20 studies examined, a majority indicated a marked enhancement in critical thinking skills (e.g., Atika et al., 2024), with certain studies employing Head-Mounted Displays (HMD) while others utilized varying VR technologies. The visualization of these findings will render a more comprehensive understanding of the efficacy of VR across diverse educational environments. Furthermore, the classification of the methodologies employed (e.g., experimental versus observational) may yield valuable insights into the most effective research paradigms for evaluating the influence of VR.

Contextual Discussion and Implications

It is imperative to account for the disparities in educational contexts when assessing the effectiveness of VR applications. For instance, the implementation of VR in secondary education may encounter distinct challenges relative to its application in higher education institutions, particularly regarding technological infrastructure, educator proficiency, and learner preparedness. Investigations conducted in regions characterized by advanced technological frameworks (e.g., Europe) may not be directly translatable to Indonesian educational settings, which continue to grapple with constraints in access to VR resources and reliable internet connectivity.

The heterogeneity of these contexts must be duly acknowledged when formulating recommendations for VR integration in Indonesian educational institutions. While VR harbors significant potential to enrich the learning experience, its effectiveness is likely to be profoundly influenced by variables such as educator training, technological accessibility, and the capability to effectively incorporate VR within the existing curriculum.

CONCLUSION

The examination of existing literature demonstrates that virtual reality (VR) possesses considerable potential to augment the quality of learning within STEM-oriented physics education. The results suggest that VR facilitates a deeper comprehension of abstract physical concepts among students. Furthermore, there exists substantial evidence indicating that VR enhances students' intrinsic motivation to learn. It also fosters their collaborative abilities and critical thinking skills—competencies that are indispensable in the contemporary digital era. By immersing students in substantial and profound experiences, VR renders the learning process more interactive and engaging. Nonetheless, despite its encouraging prospects, VR encounters numerous challenges that necessitate resolution. The most urgent concern pertains to the elevated costs associated with VR devices and the restricted accessibility of these technologies in educational institutions, particularly in remote rural regions. To guarantee the effective implementation of VR in pedagogical practices, educators require supplementary training. Consequently, it is imperative to offer more affordable VR devices, along with comprehensive training programmes for teachers. Additional research is warranted to investigate the applicability of VR across diverse subjects and educational tiers. Moreover, the formulation of systematic and effective strategies to enhance school access to VR technology is of paramount importance. To cultivate a more interactive and innovative future, the integration of VR into STEM-focused physics education necessitates broader support from various stakeholders, including governmental bodies and technology providers.

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