Lensa: Jurnal Kependidikan Fisika
Penerbit: Universitas Pendidikan Mandalika
https://e-journal.undikma.ac.id/index.php/Lensa/index

June 2026, Vol. 14, No. 1
e-ISSN: 2686-0937
pp. 101–136

Virtual Reality for Physics Learning: A Thematic Review with Cross-Disciplinary Insights on Effectiveness, Immersion, Instructional Design, and Implementation Challenges

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Abstract

Virtual reality (VR) has gained increasing attention in education, particularly for learning contexts that involve abstract concepts, dynamic processes, and simulation-based experiences. This study presents a structured thematic review of 33 Scopus-indexed articles published between 2021 and 2026, focusing on physics learning while incorporating cross-disciplinary studies as conceptual support. The review examined five major themes: effectiveness in improving learning outcomes and conceptual understanding, immersion and embodiment, suitability for abstract and high-risk contexts, the role of instructional design and usability, and implementation challenges and future directions. The findings indicate that VR is especially beneficial for physics topics such as projectile motion, quantum physics, the photoelectric effect, electric fields, and virtual laboratory activities, where visualization and interaction are essential. Across the reviewed studies, VR was consistently associated with gains in conceptual understanding, engagement, retention, motivation, and learner confidence, although these effects were conditional rather than universal. The review also shows that immersion alone is insufficient; educational effectiveness depends heavily on instructional coherence, usability, intuitive interaction, and contextual fit. Despite its promise, broader implementation remains constrained by cost, infrastructure, teacher readiness, and uneven methodological quality. Overall, VR emerges as a powerful but context-sensitive pedagogical approach for physics learning in contemporary educational and training settings.

Keywords: Virtual reality; Physics learning; Conceptual understanding; Immersion; Instructional design; Thematic review

How to cite: Dosol-Demonteverde, M. G., & Barrios, R. G. (2026). Virtual Reality for Physics Learning: A Thematic Review with Cross-Disciplinary Insights on Effectiveness, Immersion, Instructional Design, and Implementation Challenges. *Lensa: Jurnal Kependidikan Fisika*, *14*(1), 101–136. https://doi.org/10.33394/j-lkf.v14i1.20166

INTRODUCTION

The development of virtual reality (VR) in education has marked an important shift from its initial function as an attractive visual medium toward a more substantive role as a learning environment capable of reshaping learners' experiences. In this context, VR is no longer understood merely as a three-dimensional digital presentation tool, but as a medium that enables learners to interact directly with objects, phenomena, and procedures that are difficult to present through conventional instruction. Findings from a number of studies indicate that VR is increasingly used to support learning activities that require visualization, simulation, object manipulation, and active learner engagement. However, the literature also shows that the effectiveness of VR is not automatic. Its success is strongly influenced by the suitability of the content, the quality of instructional design, the form of interaction, and the learning indicators used to evaluate its impact (Hamilton et al., 2021; Holly et al., 2021; Abdullah et al., 2025).

In physics education, the need for learning approaches that can bridge abstract concepts with more concrete learning experiences is a particularly prominent issue. Many physics concepts, such as projectile motion, the photoelectric effect, electric fields, acceleration, and quantum physics, require visualization skills, spatial reasoning, and an understanding of dynamic relationships that are often difficult to achieve through lectures, formulas, or static diagrams alone. It is in this context that VR becomes especially relevant. Various studies have shown that VR can help learners develop deeper understanding of physics concepts through immersive and interactive simulations. For example, studies on projectile motion have reported improvements in conceptual understanding and learning gains after the use of immersive VR-based serious games (Tito et al., 2023; Villada, Bohorquez, & Martínez, 2025; Villada, Montoya, & Mendez, 2026). Likewise, the development of virtual laboratories for quantum physics and the photoelectric effect has demonstrated that VR can translate abstract and invisible phenomena into learning experiences that are easier to understand and more meaningful for students (Bancong & Nanda, 2025; Mufit, Hendriyani, & Dhanil, 2024; Mufit, Dhanil, & Hendriyani, 2025).

Even so, the available empirical evidence does not support a simple claim that VR is always superior to non-VR approaches. Most studies do report positive results, particularly in terms of improved conceptual understanding, knowledge retention, motivation, engagement, confidence, and quality of learning experience. However, these benefits tend to be stronger in materials that are abstract, difficult to visualize, or risky to practice directly. In a comparative study between VR laboratories and traditional hands-on laboratories, for example, the VR group showed higher knowledge retention and greater learning engagement, but did not always demonstrate the same advantage in immediate post-instruction understanding (Akdag, Botev, & Rothkugel, 2025). Similarly, studies on VR-based chemistry and physics laboratories showed that virtual environments can enhance learning experiences and knowledge retention, but this success was closely tied to ease of use and the overall quality of the system developed (Naz et al., 2024). Therefore, a more careful reading is necessary so that discussions of VR do not fall into excessive technological optimism.

Another highly prominent issue in the literature is that the pedagogical strength of VR is closely related to immersion, embodiment, and interactivity. VR becomes valuable not merely because it is new or visually impressive, but because it allows learners to feel present within the learning environment, manipulate objects, receive feedback, and engage through meaningful actions. In a study on embodied immersive VR, students were able to connect their prior knowledge with concepts of electric fields and charged particle behavior through experiences that were more spatial and interactive (Acevedo et al., 2024). Other studies found that the quality of embodiment was influenced more by body control and object manipulation than by avatar customization alone (Langener et al., 2022). Beyond physics, haptic simulators for medical training and sensory-feedback gloves showed that multisensory interaction can strengthen engagement, coordination, and learner confidence (Maraza-Quispe & Palo-Rosas, 2025; Woo et al., 2025). These findings are important for physics learning because they suggest that the quality of bodily experience and interaction can shape how learners construct scientific meaning.

In addition to abstract topics, VR also appears highly appropriate for complex and high-risk learning contexts. This can be seen in studies on transmission tower inspection, steam generator operator training, assembly and maintenance of ITER-type mock-ups, and solar PV infrastructure control using cognitive digital twins. In all of these contexts, VR was used to create safe, controlled, and repeatable training environments without exposing learners to direct risks or high operational costs (Li et al., 2021; Mantelli et al., 2023; Chae & Ko, 2024; Mamodiya et al., 2025). Although these studies do not focus directly on physics learning in schools or universities, their contributions remain important as cross-disciplinary insights. They illustrate the general principle that VR is particularly useful when learning requires representations of dynamic processes, procedural decision-making, and simulations of conditions that are difficult to reproduce in ordinary classrooms. This cross-disciplinary perspective is therefore important for enriching the understanding of how and why VR can be effective in physics learning.

Despite its growing potential, the literature also emphasizes that the effectiveness of VR is strongly shaped by instructional design, usability, and user experience. Several studies show that effective VR environments consistently have clear learning objectives, well-structured tasks, intuitive navigation, and comfortable controls (Holly et al., 2021; Liu & Liu, 2025; Zöllner et al., 2025). In the development of the Fisikawaii Adventure platform, high scores in content validity, media validity, and student responses indicated that instructional feasibility is determined not only by VR technology itself, but also by the quality of the learning design (Faqih et al., 2023). Similar patterns were found in studies of quantum physics laboratories and photoelectric effect prototypes, where validity, practicality, scientific accuracy, and visual quality were essential factors in the educational value of the media (Bancong & Nanda, 2025; Mufit, Dhanil, & Hendriyani, 2025). Thus, discussions of VR in physics education need to move beyond the question of whether VR is effective and toward the more precise question of what design conditions enable VR to function pedagogically.

Based on this background, this study aims to examine thematically how VR contributes to physics learning, while at the same time drawing on non-physics studies as conceptual support and comparative perspectives in understanding effectiveness, immersion, instructional design, and implementation challenges. Accordingly, this review does not place all studies on equal footing, but positions physics learning as the core of the analysis, while cross-disciplinary findings are used to enrich theoretical and practical interpretation. The research questions of this review are formulated as follows:

1. How effective is VR in improving learning outcomes and conceptual understanding, particularly in physics learning?
2. How do immersion, embodiment, and engagement shape the quality of VR-based learning experiences?
3. Why does VR appear especially suitable for abstract, complex, and high-risk topics in learning and training?

4. To what extent do instructional design, usability, and user experience determine the pedagogical success of VR?
5. What implementation challenges most frequently arise in the use of VR, and where is research on VR in education heading?

Novelty of the Study

A key novelty of this study is its positioning of physics learning as the primary analytical focus, rather than treating it as merely one application area of virtual reality in education. Many previous reviews have discussed VR in education in general or emphasized its broad technological benefits, but have not explicitly structured the discussion by making physics the center of analysis while still allowing room for cross-disciplinary insights. In this study, findings from contexts such as medical training, operator training, mixed reality, and avatar interaction are not used to shift the focus away from physics, but rather to clarify conceptual mechanisms that are also relevant to physics learning, such as embodied interaction, usability, rehearsal in safe environments, and task-specific simulation (Langener et al., 2022; Maraza-Quispe & Palo-Rosas, 2025; Mamodiya et al., 2025). This positioning makes the review more focused substantively while remaining conceptually rich.

Another novelty of this study is the use of a thematic framework that integrates five main dimensions: effectiveness, immersion, suitability for abstract and high-risk contexts, instructional design and usability, and implementation challenges and future directions. This framework enables a more analytical discussion than a simple inventory of research findings. Through this framework, the review does not merely answer whether VR is effective, but also explains when, for what purposes, and under what conditions VR makes the most meaningful contribution to physics learning. Therefore, this study is expected to contribute both theoretically, by sharpening understanding of the pedagogical mechanisms of VR, and practically, by providing an argumentative basis for the development of more contextual, well-designed, and realistically implementable VR-based physics learning media and strategies.

METHODS

Research Design

This study employed a structured thematic review to examine major patterns, recurrent findings, and key issues related to the use of virtual reality (VR) in learning, with physics learning positioned as the primary analytical focus. This approach was selected because the purpose of the study was not to calculate pooled effect sizes, as in a meta-analysis, but to identify, compare, and interpret the dominant themes emerging from relevant literature. Accordingly, the review was designed to generate a conceptual and pedagogical synthesis rather than a statistical aggregation of findings.

Methodologically, the review was theme-focused. The analysis was not intended to map all possible uses of VR in education in general, but to address how VR supports physics learning, under what conditions it is most beneficial, and which factors shape its effectiveness or limitations. Within this framework, studies from non-physics domains were not treated as the core of the review; instead, they were used as conceptual support and analytical comparators when they offered relevant insights into effectiveness, immersion, usability, instructional design, and implementation challenges.

Data Source and Search Strategy

All studies were identified through the Scopus database. The search focused on English-language journal articles published between 2021 and 2026. The search strategy was designed to capture studies addressing the use of VR in the context of physics learning, particularly in relation to higher-order thinking processes. The core search query used in Scopus was as follows: *[TITLE-ABS-KEY]: ((“virtual reality” OR VR OR “immersive virtual reality”) AND (“physics education” OR “physics learning” OR “physics instruction”) AND (“critical thinking” OR “problem solving” OR “scientific reasoning” OR “higher order thinking skills” OR “thinking skills”))*

In addition to the main query, the search was limited to English-language, final-stage, and journal article publications. The search results were then exported in CSV format to facilitate screening, data extraction, and the organization of bibliographic metadata and abstracts.

Although the initial search strategy was mainly designed to retrieve studies on VR in physics learning and thinking skills, the review did not rely solely on mechanical query-based selection. After the initial retrieval, substantive screening of titles and abstracts was conducted to identify studies directly relevant to physics learning, while also retaining cross-disciplinary studies that contributed conceptually to the main themes of the review, such as immersion, embodiment, usability, simulation-based learning, instructional design, and implementation challenges. Through this process, the final corpus consisted of 33 articles analyzed thematically.

Inclusion and Exclusion Criteria

Articles were included in the review if they met the following criteria. First, they addressed the use of VR, immersive VR, mixed reality, or related immersive technologies in learning, training, or user experience within educational or simulation-based training contexts. Second, studies directly focused on physics learning, virtual physics laboratories, physics serious games, or abstract physics concepts were given primary priority in the synthesis. Third, studies from non-physics domains were also included when they offered conceptually relevant insights into the central concerns of the review, particularly those related to embodied interaction, haptic feedback, simulation-based training, usability, user experience, or technology adoption barriers. Fourth, articles had to provide sufficiently informative abstracts to support the identification of objectives, methods, and main findings.

Articles were excluded if they did not demonstrate adequate relevance to the use of VR in learning or training, or if the information available in the title and abstract was insufficient to support thematic analysis. Based on these criteria, the studies retained in the final corpus were not only topically relevant but also sufficiently informative to support meaningful synthesis.

Study Selection Procedure

The methodological flow of the review is presented in Figure 1. The Figure 1 presents the main stages of the review process, including research design, data source and search strategy, identification and initial screening, eligibility assessment, study selection, data extraction, thematic synthesis, and analytical output. Physics learning was treated as the core analytical domain, while cross-disciplinary studies were used as conceptual support.

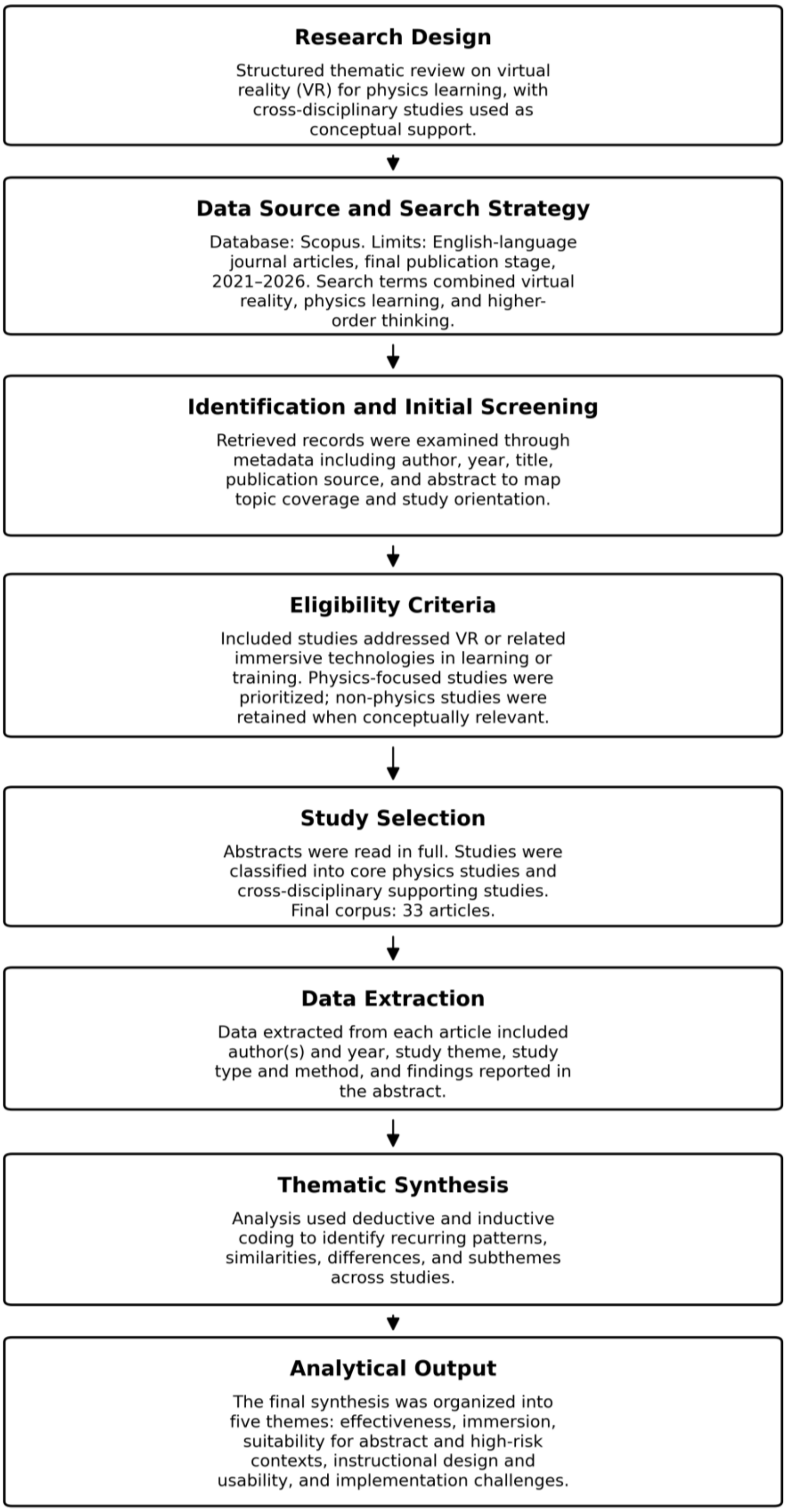

Figure 1. Methodological flow of the structured thematic review

Study selection was conducted in several stages. In the first stage, all retrieved records were examined based on basic metadata, including author names, publication year, article title, publication source, and abstract. This stage aimed to generate an initial overview of topic coverage, disciplinary domain, and methodological orientation across the identified studies.

In the second stage, the abstract of each article was read in full to assess its relevance to the focus of the review. At this stage, studies directly addressing physics learning, virtual physics laboratories, physics serious games, and abstract physics concepts were classified as core studies. Meanwhile, studies from other domains such as chemistry, medical training, operator training, mixed reality, avatar interaction, and interface design were classified as cross-disciplinary supporting studies when they made an analytical contribution to the review themes.

In the third stage, the studies that passed the final screening were organized into the analytical corpus. This selection logic was important because it established physics learning as the center of the synthesis, while non-physics studies were retained to strengthen conceptual interpretation and broaden the discussion in a controlled way. Based on this process, 33 articles were included in the final analysis.

Data Extraction Procedure

Once the final corpus had been established, data were extracted systematically from each article. The extracted information included author(s) and year, study theme, study type and method, and findings. Data extraction was based primarily on the information available in the abstracts, as Scopus abstracts generally provided concise summaries of study aims, methods, and key results.

Findings were extracted in two categories. The first category consisted of numerical indicators, such as learning gain, effect size, validity score, practicality score, percentage improvement, usability score, or other performance indicators reported in the abstract. The second category consisted of substantive descriptions, namely narrative findings explaining how VR influenced conceptual understanding, engagement, confidence, safety, usability, motivation, or user experience. For the purposes of narrative synthesis, these two categories were later integrated into a unified findings category so that each study could be interpreted more holistically.

Data Analysis Procedure

The data were analyzed using thematic synthesis. In the first stage of analysis, all studies were reread to identify recurring patterns, similarities, and differences across the articles. The findings were then coded thematically using a combination of deductive and inductive approaches.

Deductively, the analysis was guided by five major themes that later structured the results and discussion: (1) effectiveness of VR in improving learning outcomes and conceptual understanding, (2) immersion, embodiment, and engagement in VR-based learning, (3) suitability of VR for abstract, complex, and high-risk learning contexts, (4) the importance of instructional design, usability, and user experience, and (5) implementation challenges and future directions of VR in education. These five themes were selected because they appeared most consistently across the corpus and were most closely aligned with the study objectives.

Inductively, each major theme was examined in greater detail to identify emergent subthemes. For example, within the effectiveness theme, subthemes such as conceptual gain, retention, and the mediation of abstract understanding emerged. Within the immersion theme, subthemes related to embodiment, multisensory interaction, and serious-game engagement became apparent. Within the instructional design theme, subthemes such as user-centered design, task clarity, validity, practicality, and usability were identified. This approach enabled the synthesis not only to group studies into thematic categories, but also to explain how and why certain patterns emerged across different contexts.

Position of Physics Studies and the Function of Cross-Disciplinary Studies

Because this review was explicitly centered on physics learning, interpretive emphasis was placed on studies directly related to physics education. These articles served as the primary basis for developing arguments about VR effectiveness, conceptual understanding, and the suitability of VR for abstract, dynamic, and difficult-to-visualize physics content.

By contrast, studies from non-physics domains were used selectively to extend the discussion when they offered conceptually relevant insights, such as those concerning embodiment, haptic interaction, procedural rehearsal, continuance intention, user experience, or implementation barriers. This strategy was adopted to ensure that the review remained focused on physics while still benefiting from broader cross-disciplinary developments that could enrich the explanation of how VR functions as a learning and training environment.

Analytical Reliability and Study Limitations

To maintain interpretive consistency, the processes of reading, data extraction, and thematic grouping were conducted iteratively until stable patterns were identified across the studies. Final themes were not established on the basis of one or two isolated articles, but rather on recurring tendencies found throughout the corpus. In this way, the synthesis was grounded in collective patterns rather than single-study claims.

Nevertheless, this study has several limitations. First, the corpus was constructed from studies identified through Scopus, meaning that the scope of the review depended on the representation of documents within that database. Second, the synthesis relied primarily on metadata and abstracts rather than full-text analysis of all included articles. Third, the study did not conduct a formal methodological quality appraisal of each article, as would be expected in a highly rigorous systematic review. Therefore, this study is more appropriately understood as a structured thematic review aimed at producing conceptual and pedagogical synthesis, rather than a quantitative systematic review or meta-analysis.

Methodological Strengths of the Study

A key methodological strength of this study lies in its use of a structured thematic review, which allowed the synthesis to be conducted systematically while remaining flexible enough to accommodate the diversity of research designs, contexts, and forms of VR implementation represented in the corpus. This was particularly relevant because the included studies ranged from systematic reviews and quasi-experiments to development research, feasibility studies, user studies, and conceptual papers. In addition, the study explicitly positioned physics learning as the main focus, thereby giving the synthesis a clear analytical direction. At the same time, cross-disciplinary studies were incorporated selectively as conceptual support and analytical comparators, allowing the review to remain centered on physics while still drawing on broader developments in VR research.

Another strength of the study was its data extraction and analysis strategy, which integrated both numerical indicators and substantive descriptions from each article. This made it possible to capture not only quantitative evidence such as learning gain, effect size, validity, practicality, and usability, but also the pedagogical meaning behind those findings. The use of five major themes as the analytical framework further strengthened the coherence of the synthesis, as it enabled the study to examine the relationships among effectiveness, immersion, context of use, design quality, and implementation challenges in a more integrated manner. Thus, the methodological strength of this study lies in its analytical focus, thematic coherence, and ability to connect evidence from different contexts into a synthesis that remains relevant to physics learning.

RESULTS AND DISCUSSION

The results of the thematic review are based on 33 selected studies, and the dominant patterns emerging from the corpus are discussed in this section. The distribution of the reviewed studies by publication year and domain is presented in Figure 2. As shown in the figure, the corpus spans the period from 2021 to 2026 and is dominated by physics-related studies, which form the core of the review. At the same time, a smaller number of studies from chemistry, medical training, technical and operator training, and broader cross-disciplinary VR contexts were retained to provide conceptual support and comparative insights. This distribution is consistent with the analytical position of the review, in which physics learning serves as the primary focus, while non-physics studies enrich the interpretation of immersion, embodiment, usability, instructional design, and implementation challenges.

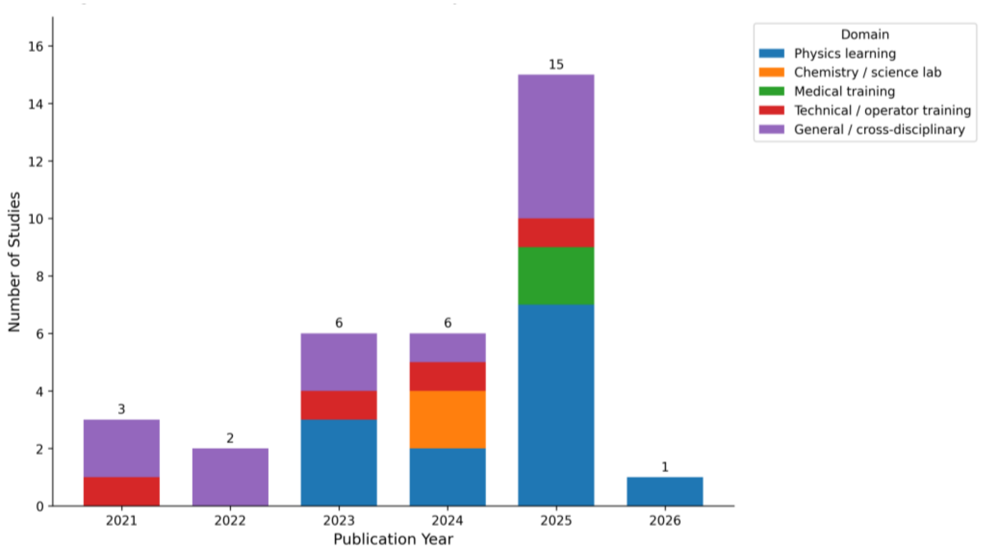

Figure 2. Distribution of reviewed studies by publication year and domain

The Figure 2 shows the distribution of the 33 reviewed studies across publication years and research domains. Physics-related studies constituted the core of the corpus, while studies from chemistry, medical training, technical and operator training, and general cross-disciplinary VR contexts were included as conceptual support and analytical comparison.

The temporal and domain-based distribution shown in Figure 2 also indicates that research on VR has become increasingly concentrated in recent years, reflecting a broader shift from exploratory discussions of VR's educational potential toward more applied and domain-specific investigations. This trend is particularly visible in studies addressing virtual physics laboratories, immersive serious games, simulation-based training, haptic interaction, and mixed-reality learning environments. Building on this overview, Table 1 provides the detailed analytical foundation for the discussion that follows by summarizing the author(s) and year, study theme, study type and method, and key findings of each included article. A close reading of these studies indicates that VR is increasingly positioned not merely as a visually engaging technology, but as a learning environment capable of supporting conceptual understanding, engagement, simulation-based practice, and complex skill development. At the same time, the evidence suggests that its educational value is conditional rather than automatic, depending on the nature of the content, the design of interaction, the usability of the system, and the context of implementation. These patterns form the basis for the five thematic discussions developed in the subsequent subsections.

Table 1. Summary of the reviewed studies on virtual reality for physics learning and related cross-disciplinary contexts.

No.	Author(s) and Year	Study Theme	Study Type and Method	Findings
1	Hamilton et al. (2021)	A systematic review of immersive VR use in education	Systematic literature review of 29 publications with quality appraisal using MERSQI	Most studies reported better learning outcomes with immersive VR, while only 2 studies reported clearly negative effects. The review also showed that many studies still had weaknesses in experimental design and outcome measurement.
2	Holly et al. (2021)	User expectations regarding the design of teaching and learning experiences in VR	Descriptive study over six months on the Maroon platform with 85 participants, including 26 student teachers and 59 pupils	The study mapped teacher and student expectations toward VR learning environments. The findings show that educational VR design needs to balance user experience, ease of use, and pedagogical considerations.
3	Li et al. (2021)	A VR-based assembly and maintenance training platform	System development and engineering study	The platform provides 3D visualization, real-time collision detection, ray-casting, and support

No.	Author(s) and Year	Study Theme	Study Type and Method	Findings
		for ITER-type mock-ups	of a virtual training platform	for remote collaborative work. The system was considered relevant for technical training in complex assembly and maintenance environments.
4	Langener et al. (2022)	Immersive VR avatars for embodiment illusion in individuals with mild to borderline intellectual disability	User-centered development and feasibility study with 29 users across 3 iterations and 5 interaction tasks	Embodiment illusion was successfully induced in participants. Body control proved more important than avatar customization, object manipulation produced the highest embodiment experience, and unrealistic interaction tended to reduce the quality of the user experience.
5	Vallance & Towndrow (2022)	Narrative storyliving in virtual reality design	Conceptual perspective article using theoretical analysis based on Bakhtin's chronotope framework	The article argues that VR should be understood as a storyliving space, meaning a space that allows participants to construct personal narratives and meaning actively rather than merely follow a predetermined storyline.
6	Faqih et al. (2023)	Gamification and virtual reality through the Fisikawaii Adventure LMS to increase learning participation	ADDIE-based development research with expert evaluation and student responses	Material expert validity reached 85.5%, media expert validity reached 87.25%, and student responses reached 86.4%. The product was considered highly feasible and had the potential to increase student participation in physics learning.
7	Gervasi, Perri, & Simonetti (2023)	The impact of VR and AR on secondary school learning	Comparative field study using questionnaires before and after VR/AR experiences with 162 students	A total of 94.43% of students considered AR useful for education. Both VR and AR were perceived as intuitive and immersive,

No.	Author(s) and Year	Study Theme	Study Type and Method	Findings
				although face-to-face learning was still considered more effective because it encouraged student collaboration.
8	Mantelli et al. (2023)	Integration of dynamic models and VR for steam generator operator training	Development of a VR platform integrated with MATLAB-Simulink dynamic models and Unity	The platform enabled intuitive simulation of both normal and emergency operating conditions. The system has the potential to improve training safety, the effectiveness of competency certification, and mastery of technical procedures.
9	Reda et al. (2023)	Physics-based motion retargeting from limited sensor input for AR/VR avatars	Development of a machine learning method using reinforcement learning, motion capture, and ablation studies	The method enabled avatars with different body morphologies to follow user motion convincingly even when lower-body sensor input was unavailable. This shows strong potential for more sensor-efficient virtual interaction applications.
10	Sarapak et al. (2023)	Needs analysis of high school teachers regarding the use of 3D virtual physics laboratories	Descriptive survey and needs analysis using a 41-item questionnaire administered to 44 teachers, analyzed with mean, SD, and PNIModified	The instrument was validated by 5 experts with a reliability value of 0.97. The highest-priority needs were spectral studies of hot gases, parallax, light interference, polarization, and diffraction and diffraction grating. Readiness for instructional management was at a moderate level, while the need for computer-assisted teaching materials and 3D virtual laboratories was high.
11	Tito, Coluci, & Moraes (2023)	The ORUN-VR serious game for	Design, development, and	Students who played ORUN-VR showed an

No.	Author(s) and Year	Study Theme	Study Type and Method	Findings
		projectile kinematics learning	testing with more than 130 high school students using knowledge tests, usability, engagement, and presence measures	overall learning gain of 52% compared with students who did not play. In addition to improved learning outcomes, students also demonstrated positive engagement and sense of presence during the learning experience.
12	Acevedo et al. (2024)	Embodied immersive virtual reality for understanding charged particles	Qualitative study with 8 students using pretest-posttest, interviews, screen recordings, and SUS	Students were able to recognize the designed affordances in the IVR environment and connect the experience to their prior knowledge. The embodied experience helped participants explain electric field concepts and charged particle behavior more effectively.
13	Chae & Ko (2024)	A physics-based virtual training simulator for steel transmission tower inspection	Development of a VR simulator integrating drone physics factors and user evaluation	The simulator provided immersive training, supported multi-user operation, and helped users understand complex and high-risk inspection tasks. It also addressed field training limitations related to drone battery life and operational risk.
14	Lu et al. (2024)	A VR- and gesture-interaction-based chemistry simulation teaching system	System development using Blender, 3DS MAX, a physics engine, gesture hardware, and comparative evaluation	The proposed system was considered better than two market products in terms of fidelity and practicality. In addition to supporting safer and more interactive experiments, the system was also seen as having strong potential for chemistry learning in secondary schools and distance education.

No.	Author(s) and Year	Study Theme	Study Type and Method	Findings
15	Mufit, Hendriyani, & Dhanil (2024)	Design of immersive VR with cognitive conflict for quantum physics practicum	Design research with needs analysis, media development, validation by 6 experts, and practicality testing with 9 students	The needs analysis involved 97 students. The validity of the learning and material aspects reached 0.89, media validity reached 0.95, and average practicality reached 92. The cognitive-conflict-based IVR design was considered valid and highly practical for supporting quantum physics practicum.
16	Naz et al. (2024)	Development and evaluation of immersive VR laboratories for organic chemistry and physics	Development of VR simulations and usability evaluation, followed by a comparative study of VR and traditional groups	The average scores for the VR chemistry laboratory and VR physics laboratory reached 92.63% and 93.38%, respectively. A comparative study involving 20 students in the VR group and 13 students in the traditional group showed that the VR group had better learning experience and stronger knowledge retention. All participants in the experimental group also reported that the virtual lab was easy to use.
17	Tessler et al. (2024)	Physics-based character control through masked motion inpainting	Development of an AI method with a unified model trained for multiple control modalities	MaskedMimic allowed a single controller to support multiple control modalities simultaneously and enabled smooth task transitions. This approach improved the flexibility of virtual characters in handling complex interactive scenarios.
18	Abdullah et al. (2025)	SWOT analysis of the impact of VR on engagement	Descriptive conceptual study	VR was considered strong in improving engagement,

No.	Author(s) and Year	Study Theme	Study Type and Method	Findings
		and learning outcomes	using a SWOT framework	motivation, critical thinking, skill acquisition, and inclusiveness. At the same time, its implementation still faces barriers such as cost, motion sickness, infrastructure limitations, and educator hesitation, although the opportunities for distance learning and interdisciplinary use remain substantial.
19	Akdag, Botev, & Rothkugel (2025)	Comparison of VR and traditional hands-on laboratories for abstract physics concepts	Controlled comparative study between a VR-based physics lab and traditional electronic kits	The VR group showed higher knowledge retention and longer learning engagement time. Meanwhile, immediate post-learning understanding did not show a meaningful difference between the two groups.
20	Bancong & Nanda (2025)	Development and validation of a VR prototype for photoelectric effect experiments	Development research with iterative design and expert validation	The prototype was judged strong in scientific accuracy, educational value, engagement, and visual quality. The media was able to simulate the photoelectric effect safely and flexibly, and was positioned as a complement to real laboratories.
21	Grandi et al. (2025)	A wearable ultrasound interface for hand and wrist tracking in VR	Device and deep learning model development with intra-session, cross-session, cross-participant, and real-time evaluation	The portable ultrasound armband was able to predict hand and wrist kinematics accurately for new users without additional fine-tuning. The technology was considered feasible for more natural and flexible real-time VR interaction.

No.	Author(s) and Year	Study Theme	Study Type and Method	Findings
22	Kobilova et al. (2025)	The role of VR/AR in improving scientific literacy and science learning motivation	Quasi-experimental pretest-posttest design with a control group, supported by surveys, observations, and interviews	Students who learned through immersive media showed better academic performance and stronger concept application, higher motivation, and more active classroom interaction. Teachers also reported better questioning and collaboration compared with conventional instruction.
23	Kurbanbekov et al. (2025)	The impact of VR on physics teaching in the topic of body acceleration	Quasi-experimental study with 222 students using pretest-posttest and independent t-test analysis	VR-based instruction improved learning outcomes, engagement, conceptual understanding, and students' ability to connect theory with practical applications. These findings support the use of VR as an effective approach in physics education.
24	Liu & Liu (2025)	Effects of knowledge visualization and user experience on continuance intention in mixed-reality STEM learning	Experiment with 136 high school students using structural equation modeling based on partial least squares	The model explained 65.2% of the variance in system usability, 53.4% in satisfaction, 51.5% in perceived enjoyment, 54.9% in attitude, and 63.2% in continuance intention. These results show that usability and positive learning experience play major roles in sustaining student engagement in mixed-reality STEM learning.
25	Mamodiya et al. (2025)	A VR-based cognitive digital twin for interactive control of solar PV infrastructure	Framework development combining physics-informed models, deep learning surrogates, reinforcement learning, drift	The framework achieved an NRMSE of 8.9%, detected drift within 90 seconds, and recorded a P95 response latency of 382 ms. Operator task completion time

No.	Author(s) and Year	Study Theme	Study Type and Method	Findings
			detection, and operator testing	decreased by 27% and workload decreased by 22% compared with conventional SCADA platforms. The system improved control resilience, transparency, and human-in-the-loop decision support.
26	Maraza-Quispe & Palo-Rosas (2025)	VR with sensory feedback gloves for medical training	Quasi-experimental study with 50 medical students divided into control and experimental groups, analyzed using t-tests, ANCOVA, and repeated-measures ANOVA	Instrument reliability ranged from alpha = 0.83 to 0.88. The experimental group showed highly significant improvement with $p < 0.001$ and effect sizes up to $\eta 2$ = 0.86. The use of VR with sensory gloves improved movement precision, visuomotor coordination, sequencing, safety, confidence, and learning motivation.
27	Mathew et al. (2025)	An AR/VR virtual laboratory for simple pendulum learning	Design, implementation, and evaluation using pretest-posttest with 100 students	Conceptual understanding increased from 62% to 80%, skill development from 55% to 78%, and engagement and motivation from 58% to 82%. PO1 increased from 2.2 to 2.8, PO2 reached 3.0, PO3 increased by 0.7 points, and the average gravitational value obtained was 9.85 m/s2. These results show that the virtual laboratory was effective in improving physics learning outcomes.
28	Mufit, Dhanil, & Hendriyani (2025)	Development of an immersive virtual reality quantum physics laboratory	Development research through needs analysis, design, implementation,	The needs analysis involved 97 students. The product obtained a validity score of 0.92 and a practicality score of 92.25%. The virtual

No.	Author(s) and Year	Study Theme	Study Type and Method	Findings
			validity testing, and practicality testing	laboratory was considered an innovative solution for visualizing abstract quantum phenomena and supporting student conceptual understanding.
29	Villada, Bohorquez, & Martínez (2025)	Effectiveness of an immersive virtual reality serious game for projectile motion learning	One-group pretest-posttest experiment with 17 students, analyzed using the Wilcoxon signed-rank test	There was a significant improvement in conceptual understanding after the intervention, with $p = 0.007$ and $Z = -2.687$. The IVR serious game helped students connect immersive experience with stronger understanding of projectile motion concepts.
30	Woo et al. (2025)	A bimanual haptic VR simulator for IV needle insertion training	Development of a Unity-based simulator and a 3-week experiment with 41 participants	The success rate increased by 55% after simulator use. In addition to better performance, participants also showed higher confidence, and the simulator was considered effective as a repeatable and scalable training medium.
31	Zhao et al. (2025)	Deep learning for efficient full-color hologram generation in immersive displays	Development of a computational method using a multi-scale residual CNN and evaluation through simulations and optical experiments	The model achieved average PSNR values of 34.52 dB for RGB-D, 33.80 dB for YCbCr-Holo1/2, and 32.56 dB for YCbCr-Holo1/4. GPU inference time decreased from 12 ms to 6 ms and 4 ms, while GPU memory usage decreased from 3212.90 MB to 1960.97 MB and 1162.79 MB. The system accelerated the process by up to three times while still

No.	Author(s) and Year	Study Theme	Study Type and Method	Findings
				producing sharp reconstructions and natural colors.
32	Zöllner et al. (2025)	Interactive nuclide chart visualization in VR for physics education	Design of four VR interaction variants and a user study with 24 participants	Among the four variants tested, the wall-controller model was the most preferred in terms of usability and user experience. The findings indicate that interaction design strongly influences the effectiveness of exploring abstract content in VR.
33	Villada, Montoya, & Mendez (2026)	Design, evaluation, and conceptual impact of an IVR serious game for projectile motion	User-centered design with two playtesting sessions and a pilot study with 17 students using Meta Quest 2	The average normalized learning gain reached 0.68 according to Hake, the effect size was very large with d = 2.83, and the proportion of students reaching the conceptual competency threshold increased from 12% to 100%. The iterative design process also improved gameplay, immersion, and instructional clarity.

Overall, the pattern emerging from the 33 reviewed studies suggests that virtual reality is increasingly positioned not merely as an attractive visual medium, but as a learning environment capable of reshaping how learners interact with concepts, procedures, and learning situations. At the same time, this pattern should not be simplified into the claim that VR is always superior to non-VR approaches. Most studies do report positive effects on conceptual understanding, retention, motivation, engagement, usability, or learner confidence, yet the strength of these effects appears to depend heavily on the nature of the content, the quality of interaction design, and the outcomes being measured. In the earlier studies, especially around 2021 to 2022, the discussion was still largely centered on foundational questions such as whether immersive VR was appropriate for educational use, how learners responded to it, and which design factors were necessary to make the experience not only immersive but also meaningful (Hamilton et al., 2021; Holly et al., 2021; Langener et al., 2022; Vallance & Towndrow, 2022). From 2023 to 2026, however, the direction of research became more applied and domain-specific, covering virtual physics laboratories, operator training, medical training, serious games, mixed reality, haptic feedback, and AI-supported control systems (Li et al., 2021; Mantelli et al., 2023; Mamodiya et al., 2025; Maraza-Quispe & Palo-Rosas, 2025; Woo et al., 2025). Thus, the major trend is not only an increase in the number of studies, but also a shift from exploring potential toward testing the conditions under which VR becomes pedagogically effective.

From the perspective of learning outcomes, the most visible pattern is that VR tends to show fairly consistent benefits in topics that are abstract, difficult to visualize, or risky to practice directly. This is evident in studies on projectile motion, quantum physics, the photoelectric effect, electric fields, chemistry laboratories, steam generator operation, and transmission tower inspection (Acevedo et al., 2024; Bancong & Nanda, 2025; Chae & Ko, 2024; Mufit, Hendriyani, & Dhanil, 2024; Tito et al., 2023; Villada, Bohorquez, & Martínez, 2025). In these contexts, VR functions as a bridge between conceptual representation and more concrete learning experience. Learners do not simply view diagrams or formulas, but engage with simulations that allow them to grasp spatial relations, dynamic processes, and the consequences of actions within safe and controlled environments. Even so, this trend also requires careful interpretation. Not all studies show absolute superiority of VR over traditional methods, especially when the measured outcome is immediate post-instruction understanding. In some cases, the advantage of VR is more clearly reflected in knowledge retention, duration of engagement, procedural confidence, or the overall quality of the learning experience rather than in substantially higher final scores (Akdag et al., 2025; Hamilton et al., 2021; Naz et al., 2024). In other words, the collective evidence more strongly supports the argument that VR is most powerful when it deepens and mediates understanding of complex material, rather than serving as an automatic substitute for all conventional instruction.

Another very strong trend is that the effectiveness of VR is almost always associated with immersion, embodiment, and interactivity. Many studies show that learning becomes more meaningful when users feel present within the virtual environment, can manipulate objects, receive sensory feedback, or control avatars and interfaces in natural ways. In this sense, VR seems to work not only because it is technologically novel, but because it enables a form of cognitive and affective engagement that differs from ordinary digital media. Studies on embodied learning, wearable ultrasound interfaces, haptic simulators, sensory feedback gloves, and avatar-based interaction indicate that the quality of bodily experience and interaction plays a major role in shaping learning meaning (Acevedo et al., 2024; Grandi et al., 2025; Langener et al., 2022; Maraza-Quispe & Palo-Rosas, 2025; Woo et al., 2025). However, this trend also reveals an important critical point: high interactivity does not automatically produce high-quality learning. Several findings imply that VR environments lacking clear instructional structure, intuitive navigation, and comfortable control may remain at the level of novelty effect. Learners may be impressed by the experience, yet fail to develop strong conceptual understanding. Therefore, the overall picture across the studies points to the conclusion that VR becomes educationally valuable when experience design, task design, and learning objectives are integrated coherently, not when immersion is left to operate on its own (Holly et al., 2021; Liu & Liu, 2025; Zöllner et al., 2025).

Finally, the overall trend across these 33 studies suggests that VR in education is moving toward a more mature stage, although it is not yet fully stable in terms of evidence or implementation. On the one hand, more studies now report strong numerical indicators such as learning gains, effect sizes, improved validity and practicality scores, reduced workload, or greater task efficiency, showing that VR research is no longer based solely on user perception but is increasingly attempting to build measurable evidence (Mamodiya et al., 2025; Mathew et al., 2025; Villada, Montoya, & Mendez, 2026; Zhao et al., 2025). On the other hand, the research designs remain highly heterogeneous, ranging from systematic reviews and quasi-experiments to one-group experiments, development research, feasibility studies, user studies, and conceptual papers. This variation means that the strength of conclusions differs considerably across studies. In addition, implementation barriers repeatedly appear, including equipment costs, infrastructure readiness, motion sickness, limited access, teacher preparedness, and the sustainability of long-term use in educational institutions (Abdullah et al., 2025; Gervasi et al., 2023). Thus, the main trend is not that VR has already become a final solution for education, but that it is increasingly recognized as a promising approach for particular contexts, provided that it is well designed and realistically implemented. From this perspective, the key research question is no longer whether VR is useful, but under what conditions, for which purposes, and through what forms of design VR can make the most meaningful contribution to learning.

Effectiveness of Virtual Reality (VR) in Improving Learning Outcomes and Conceptual Understanding

The findings across the reviewed studies suggest that VR has substantial potential to improve learning outcomes and conceptual understanding, but the pattern is best described as positive with qualifications rather than universally superior. A useful starting point is the systematic review by Hamilton et al. (2021), which found that most immersive VR studies reported better learning outcomes, although the strength of evidence varied and some studies still suffered from weaknesses in design and outcome measurement. This is important because it prevents an overly broad conclusion. The reviewed evidence does not show that VR automatically outperforms all conventional methods in every educational situation. Instead, the studies collectively indicate that VR is especially effective when the learning task requires visualization, simulation, and active conceptual engagement. In other words, the effectiveness of VR appears to depend not only on the technology itself, but also on the kind of knowledge being taught and the quality of the instructional design surrounding it (Hamilton et al., 2021).

A particularly consistent trend appears in physics education, where many of the reviewed studies reported measurable gains in conceptual understanding after VR-based interventions. For example, Villada, Bohorquez, and Martínez (2025) found a statistically significant improvement in students' understanding of projectile motion after using an immersive virtual reality serious game, with the Wilcoxon test showing $p = .007$ and $Z = -2.687$. Similarly, Tito, Coluci, and Moraes (2023) reported an overall learning gain of 52% among students who used the ORUN-VR serious game for projectile kinematics, compared with those who did not use the game. Strong gains were also reported by Villada, Montoya, and Mendez (2026), whose user-centered IVR game for projectile motion produced an average normalized learning gain of 0.68 and a very large effect size of $d = 2.83$, while the proportion of students reaching the conceptual competency threshold increased from 12% to

100%. Taken together, these studies suggest that VR can support not only engagement but also measurable conceptual change, especially in topics involving motion, spatial reasoning, and dynamic relationships (Tito et al., 2023; Villada, Bohorquez, & Martínez, 2025; Villada, Montoya, & Mendez, 2026).

The same pattern is visible in other science domains, especially where conceptual understanding depends on linking theory to simulation or experiment-like practice. Mathew et al. (2025) reported that in an AR/VR virtual laboratory for simple pendulum learning, conceptual understanding increased from 62% to 80%, skill development rose from 55% to 78%, and engagement and motivation increased from 58% to 82%. In quantum physics, Mufit, Hendriyani, and Dhanil (2024) and Mufit, Dhanil, and Hendriyani (2025) did not only present usability evidence, but also showed that immersive virtual laboratories were considered valid and highly practical for supporting understanding of abstract quantum phenomena. Bancong and Nanda (2025) likewise showed that a VR prototype for the photoelectric effect could simulate the phenomenon in a scientifically accurate and educationally valuable way, suggesting that conceptual comprehension can be strengthened when invisible or abstract processes are translated into interactive visual experiences. These results support the argument that VR is especially beneficial when learners must move from symbolic or formula-based representations toward deeper conceptual models of physical phenomena (Bancong & Nanda, 2025; Mathew et al., 2025; Mufit, Dhanil, & Hendriyani, 2025; Mufit, Hendriyani, & Dhanil, 2024).

However, the effectiveness of VR should not be reduced to score improvement alone. Several studies suggest that VR contributes to learning partly by making conceptual relations easier to experience and manipulate. Acevedo et al. (2024), for instance, showed that embodied immersive VR helped students connect prior knowledge with electric field concepts and charged particle behavior. Kobilova et al. (2025) similarly reported that students using VR or AR demonstrated better concept application, stronger performance, and higher motivation than those in more conventional settings. Naz et al. (2024) found that students in immersive VR laboratories for organic chemistry and physics achieved very high performance scores, 92.63% and 93.38%, respectively, and also showed better learning experience and stronger knowledge retention than the traditional group. These findings imply that VR can improve learning not simply because it is novel, but because it can support more concrete mental representations, clearer procedural sequencing, and stronger links between conceptual content and learner action. In that sense, VR appears to function as a mediating environment that can make difficult ideas more cognitively accessible (Acevedo et al., 2024; Kobilova et al., 2025; Naz et al., 2024).

At the same time, the reviewed studies also show that the gains associated with VR are not identical across all types of learning outcomes. Akdag, Botev, and Rothkugel (2025) reported that the VR group demonstrated higher knowledge retention and longer engagement time, but immediate post-learning understanding did not differ meaningfully from the traditional group. This is an important counterpoint because it suggests that VR may be especially useful for consolidation and retention rather than always producing instant superiority in short-term achievement measures. A similar nuance can be seen in the broader review by Hamilton et al. (2021), which concluded that although immersive VR often leads to positive outcomes, the evidence base is still methodologically uneven. Therefore, the reviewed studies support a careful interpretation: VR tends to improve learning outcomes most clearly when the target outcome involves retention, procedural understanding, or conceptual visualization, whereas claims about universal superiority in all assessment contexts remain too strong. This distinction is useful for discussion because it prevents the section from overstating the evidence while still recognizing the recurring positive trend (Akdag et al., 2025; Hamilton et al., 2021).

Overall, the evidence from the reviewed studies indicates that VR is an effective educational medium for improving learning outcomes and conceptual understanding, particularly in science and technical subjects where learners must understand dynamic, abstract, or experimentally difficult phenomena. The strongest evidence comes from studies reporting direct gains in concept mastery, learning gain, effect size, and post-intervention improvement, as shown in projectile motion, pendulum learning, chemistry and physics laboratories, and related scientific topics (Mathew et al., 2025; Naz et al., 2024; Tito et al., 2023; Villada, Bohorquez, & Martínez, 2025; Villada, Montoya, & Mendez, 2026). Still, the pattern across the studies suggests that VR should not be framed as inherently effective in isolation. Its value emerges when immersive features are aligned with conceptual goals, when the learning task truly benefits from simulation and visualization, and when outcomes are assessed beyond surface-level novelty. Thus, the literature supports a balanced conclusion: VR is a promising and often effective approach for improving conceptual understanding, but its pedagogical impact is strongest under well-designed and context-sensitive conditions (Akdag et al., 2025; Hamilton et al., 2021).

Immersion, Embodiment, and Engagement in VR-based Learning

A major pattern across the reviewed studies is that the value of VR in education does not rest only on content delivery, but on the way it reorganizes the learner's experience through immersion, embodiment, and active engagement. In this literature, immersion refers to the extent to which learners feel present inside a simulated environment, while embodiment refers to the sense that their body, movements, or actions are meaningfully integrated into the learning process. The studies collectively suggest that these features matter because they shift learners from passive observation toward situated participation. This is especially visible in studies where students did not merely watch content, but interacted with objects, manipulated environments, or navigated tasks through gesture, motion, or avatar-based action. Hamilton et al. (2021) already noted in their review that immersive VR often produces favorable outcomes compared with less immersive approaches, although the exact mechanisms are not always measured consistently. Across the current set of studies, the recurring implication is that immersion and embodiment are not decorative features of VR. Rather, they appear to be core mechanisms through which attention, cognitive focus, motivation, and conceptual engagement are strengthened (Hamilton et al., 2021).

The role of embodiment is particularly clear in studies that examined how bodily interaction shapes meaning-making. Acevedo et al. (2024) showed that embodied immersive VR helped students connect prior knowledge to abstract concepts related to electric fields and charged particles. Their findings suggest that when learners experience concepts through embodied interaction, they are better able to articulate and interpret complex scientific relationships. A similar point appears in Langener et al. (2022), who found that embodiment illusion could be successfully induced in users with mild to borderline intellectual disability. Their study is important because it shows that embodiment is not merely a technical effect, but a learning-relevant condition shaped by design. Body control was found to be more important than avatar customization, and object manipulation generated the strongest sense of embodiment. This implies that engagement in VR is strengthened when learners are allowed to act meaningfully in the virtual environment, rather than simply exist within it visually. In both studies, embodiment seems to support engagement by making learning experiences feel personally enacted rather than externally presented (Acevedo et al., 2024; Langener et al., 2022).

The reviewed studies also suggest that immersion becomes more educationally powerful when combined with responsive and multisensory interaction. Woo et al. (2025), for example, found that a bimanual haptic VR simulator for IV needle insertion improved success rates by 55% and also increased learner confidence. The value of this study is not limited to the performance gain. It also shows that tactile and motor engagement can intensify learner involvement by making practice more realistic and repeatable. Maraza-Quispe and Palo-Rosas (2025) reported a similar pattern in medical training with sensory feedback gloves, where the experimental group showed highly significant gains across precision, visuomotor coordination, sequencing, safety, confidence, and motivation. These studies point to a broader conclusion: engagement in VR is often deepest when learners are not only mentally attentive but physically coordinated with the learning task. In such contexts, immersion is reinforced by feedback loops between perception, movement, and task performance. This makes the learning experience feel less like viewing content and more like performing within a meaningful environment, which likely explains why many participants report high confidence and strong involvement alongside skill improvement (Maraza-Quispe & Palo-Rosas, 2025; Woo et al., 2025).

Engagement is also frequently strengthened when VR is paired with challenge, interaction, and game-like structures. Tito et al. (2023) found that students using the ORUN-VR serious game for projectile kinematics not only achieved a 52% learning gain, but also reported positive engagement and sense of presence. Similarly, Villada, Bohorquez, and Martínez (2025) showed that an immersive VR serious game significantly improved conceptual understanding of projectile motion, suggesting that the immersive format supported sustained learner attention and involvement. Faqih et al. (2023) also reported strong student responses to the Fisikawaii Adventure platform, with high feasibility ratings and evidence that gamified VR could improve participation in physics learning. These studies support the view that engagement in VR is not produced by immersion alone. It is more likely to emerge when immersion is linked to purposeful activity, challenge, and interaction design that keeps learners cognitively and emotionally invested. This is an important distinction, because it suggests that engagement is an outcome of how VR is structured pedagogically, not simply a consequence of wearing a headset or entering a 3D environment (Faqih et al., 2023; Tito et al., 2023; Villada, Bohorquez, & Martínez, 2025).

Another notable trend is that user experience variables such as usability, satisfaction, and perceived enjoyment are closely tied to immersive engagement. Liu and Liu (2025) found that system usability, satisfaction, perceived enjoyment, and attitude explained a substantial proportion of continuance intention in mixed-reality STEM learning. Their model indicates that learners remain engaged not only because the environment is technologically impressive, but because it is usable, enjoyable, and psychologically rewarding. Holly et al. (2021) similarly emphasized that educational VR design must balance user experience, ease of use, and pedagogical intent. Gervasi et al. (2023) found that students viewed VR and AR as intuitive and immersive, even if face-to-face learning was still regarded as more effective for collaboration. These studies complicate any simplistic claim that immersion automatically guarantees engagement. A highly immersive environment may still fail educationally if it is difficult to navigate, cognitively overwhelming, or disconnected from instructional goals. Therefore, the relationship among immersion, embodiment, and engagement is best understood as conditional. Immersion supports engagement most effectively when learners also experience clarity, comfort, control, and meaningful task alignment (Gervasi et al., 2023; Holly et al., 2021; Liu & Liu, 2025).

Overall, the reviewed literature supports the conclusion that immersion, embodiment, and engagement are central to the educational promise of VR, but their effectiveness depends on how they are designed and integrated into learning activities. The strongest studies do not treat immersion as spectacle. Instead, they show that presence, bodily interaction, and active participation can create conditions in which learners attend more deeply, act more deliberately, and connect more strongly with the material. This is evident in studies of embodied science learning, haptic and glove-based training, avatar interaction, serious games, and mixed-reality learning systems (Acevedo et al., 2024; Langener et al., 2022; Maraza-Quispe & Palo-Rosas, 2025; Tito et al., 2023; Woo et al., 2025). At the same time, the evidence also indicates that immersion without usability, pedagogical structure, or meaningful interaction may produce interest without sustained learning value. Thus, the literature does not support the broad assumption that more immersion is always better. Rather, it supports a more specific conclusion: immersion and embodiment enhance engagement in VR-based learning when they are connected to purposeful learner action, well-designed interfaces, and educational tasks that genuinely benefit from experiential participation (Hamilton et al., 2021; Holly et al., 2021; Liu & Liu, 2025).

Suitability of VR for Abstract, Complex, and High-Risk Learning Contexts

One of the clearest patterns across the reviewed studies is that VR appears particularly suitable for learning contexts in which the subject matter is abstract, procedurally complex, or difficult to access safely in real life. This pattern matters because it suggests that the educational value of VR is not evenly distributed across all topics. Rather than serving as a universal replacement for conventional instruction, VR seems to be most beneficial when learners need support in visualizing invisible phenomena, understanding dynamic systems, or practicing tasks that would otherwise be dangerous, expensive, or logistically difficult. Several of the reviewed studies point in this direction. In physics education, for instance, VR was repeatedly used to represent concepts that are hard to observe directly, such as projectile motion, quantum phenomena, the photoelectric effect, and electric field interactions. In technical and professional training, VR was used to simulate inspection tasks, assembly procedures, operator training, and medical practice under conditions that would be risky or resource-intensive in real settings. Taken together, these studies suggest that VR is especially well suited to contexts where reality is inaccessible, abstract, or unsafe, and where learning benefits from simulation-based approximation of real processes (Bancong & Nanda, 2025; Chae & Ko, 2024; Li et al., 2021; Mantelli et al., 2023).

The suitability of VR for abstract learning contexts is especially visible in science education, where learners often struggle to connect symbolic explanations with mental models of processes they cannot directly see. Bancong and Nanda (2025) showed that a VR prototype for the photoelectric effect could simulate the phenomenon with scientific accuracy and educational value, offering learners an interactive representation of a topic that is otherwise highly abstract. A similar pattern appears in quantum physics. Mufit, Hendriyani, and Dhanil (2024) and Mufit, Dhanil, and Hendriyani (2025) both argued that immersive virtual environments were valuable because they helped students engage with quantum concepts that are difficult to imagine through text, formulas, or static diagrams alone. Acevedo et al. (2024) also found that embodied immersive VR supported students' understanding of charged particles and electric field concepts by allowing them to connect prior knowledge with spatially meaningful experience. These studies collectively indicate that VR is particularly appropriate when the learning objective involves building conceptual understanding of phenomena that cannot be directly observed. In such cases, VR does not simply add visual appeal. It provides a representational bridge that helps learners move from abstraction toward intelligibility through interaction, embodiment, and simulation (Acevedo et al., 2024; Bancong & Nanda, 2025; Mufit, Dhanil, & Hendriyani, 2025; Mufit, Hendriyani, & Dhanil, 2024).

VR also appears highly suitable for complex learning contexts that require procedural coordination, spatial awareness, or systems thinking. Li et al. (2021) developed a VR-based assembly and maintenance training platform for ITER-type mock-ups, showing how virtual simulation can support highly specialized technical training involving 3D visualization, collision detection, and remote collaboration. Mantelli et al. (2023) similarly integrated dynamic models and VR to train steam generator operators, allowing learners to interact with normal and emergency operating conditions in an intuitive environment. Mamodiya et al. (2025) extended this line of work through a VR-based cognitive digital twin for solar PV infrastructure, where the system improved control resilience and reduced workload in a technologically complex setting. These studies suggest that VR is appropriate not only when content is abstract, but also when learning involves multiple interacting variables, real-time decisions, and procedural chains that are difficult to reproduce consistently in conventional classrooms. In such environments, VR supports the learner by simplifying access to complexity without eliminating the logic of the system itself. This is a significant strength, because it allows educational settings to approximate industrial or technical realities while maintaining a manageable learning space (Li et al., 2021; Mamodiya et al., 2025; Mantelli et al., 2023).

The value of VR becomes even more apparent in high-risk contexts, where direct practice may expose learners to danger, high costs, or severe operational constraints. Chae and Ko (2024), for example, developed a physics-based VR simulator for steel transmission tower inspection, a task that is inherently risky and constrained by drone battery life and field conditions. Their findings suggest that VR provides a viable training alternative by enabling users to rehearse inspection procedures in an immersive yet safe environment. Medical training studies reported a similar pattern. Woo et al. (2025) found that a bimanual haptic VR simulator improved IV needle insertion performance and learner confidence, while Maraza-Quispe and Palo-Rosas (2025) showed that VR with sensory feedback gloves significantly improved movement precision, coordination, sequencing, safety, and motivation among medical students. These studies indicate that VR is especially suitable when repeated practice is essential but real-world trial and error would be ethically, financially, or physically problematic. In such cases, VR functions as a safe rehearsal space where learners can make mistakes, receive feedback, and develop competence before facing real consequences (Chae & Ko, 2024; Maraza-Quispe & Palo-Rosas, 2025; Woo et al., 2025).

Another important point is that the suitability of VR in these contexts is strengthened when the environment is not only immersive, but also task-specific and pedagogically aligned. Not every difficult topic automatically benefits from VR. The reviewed studies suggest that VR becomes especially relevant when it matches the structure of the knowledge domain. For projectile motion, kinematics, and pendulum learning, for instance, the advantage of VR lies in representing motion, force, trajectory, and dynamic relationships over time (Mathew et al., 2025; Tito et al., 2023; Villada, Bohorquez, & Martínez, 2025; Villada, Montoya, & Mendez, 2026). For laboratory sciences such as chemistry and quantum physics, the strength of VR lies in its ability to model experiments that are invisible, hazardous, or difficult to repeat under normal classroom conditions (Mufit, Dhanil, & Hendriyani, 2025; Naz et al., 2024). This means that the suitability of VR is not a general property of the technology alone. It depends on whether the learning context genuinely requires simulation, visualization, procedural rehearsal, or embodied interaction. Where those conditions are present, VR appears to offer a meaningful pedagogical advantage.

The reviewed literature strongly supports the view that VR is most suitable for abstract, complex, and high-risk learning contexts. Across science education, technical training, and medical instruction, the studies consistently show that VR can make invisible phenomena more understandable, complex systems more navigable, and risky practice more accessible and safe (Acevedo et al., 2024; Chae & Ko, 2024; Li et al., 2021; Maraza-Quispe & Palo-Rosas, 2025; Mantelli et al., 2023). At the same time, the evidence also suggests a limit to this claim. VR is not equally necessary for every topic, nor is it automatically effective simply because a topic is difficult. Its greatest strength appears when the learning environment requires learners to engage with realities that are otherwise inaccessible, dangerous, or conceptually hard to construct through traditional instruction alone. Therefore, the literature supports a focused conclusion: the pedagogical value of VR is especially strong in contexts where simulation is not just helpful, but educationally necessary for bridging the gap between theory, practice, and experience.

The Importance of Instructional Design, Usability, and User Experience

Another major pattern across the reviewed studies is that the educational value of VR depends not only on immersion or technological sophistication, but on how well the learning environment is designed instructionally and how easily learners can use it. This point is important because the literature does not support the assumption that VR becomes educationally effective simply by placing students inside a virtual space. Rather, the studies suggest that VR works best when the learning objectives, interaction structure, feedback system, and interface design are carefully aligned. Hamilton et al. (2021) already noted in their systematic review that although immersive VR often produces favorable outcomes, many studies still show weaknesses in intervention design and outcome measurement. This means the discussion cannot treat VR as a self-sufficient solution. Instead, the reviewed evidence indicates that design quality is a central explanatory factor behind whether VR supports meaningful learning or merely produces short-term novelty. In this sense, instructional design, usability, and user experience are not secondary considerations. They are among the main conditions that determine whether VR contributes to conceptual understanding, engagement, and sustained educational use (Hamilton et al., 2021).

The importance of instructional design is especially visible in studies that explicitly connect learning effectiveness with the structure of the virtual task. Holly et al. (2021) found that educational VR design must balance user experience, ease of use, and pedagogical intent. Their study is useful because it shifts the discussion away from technology-centered enthusiasm and toward design-centered educational quality. A similar conclusion can be drawn from the projectile motion studies. Tito et al. (2023) and Villada, Montoya, and Mendez (2026) showed that serious games in immersive VR could improve learning outcomes, but these gains were not produced by immersion alone. They were tied to environments that were deliberately designed around instructional goals, gameplay clarity, and interaction flow. Villada, Montoya, and Mendez (2026) in particular emphasized that the iterative user-centered design process improved gameplay, immersion, and instructional clarity. This suggests that the learning benefits of VR are often the result of deliberate pedagogical scaffolding rather than the medium itself. In other words, the question is not simply whether VR is used, but whether the virtual environment is designed to guide attention, sequence activities, and help learners make sense of what they are doing (Holly et al., 2021; Tito et al., 2023; Villada, Montoya, & Mendez, 2026).

Usability is another decisive factor repeatedly highlighted in the reviewed studies. Liu and Liu (2025) showed that system usability explained a substantial proportion of key learner responses in mixed-reality STEM learning, alongside satisfaction, perceived enjoyment, and continuance intention. Their findings indicate that learners are more likely to remain engaged when the environment is not only interesting but also understandable and manageable. Naz et al. (2024) similarly found that all participants in the experimental group considered the virtual laboratories easy to use, while the VR chemistry and physics labs achieved very high performance scores. Gervasi et al. (2023) reported that students perceived VR and

AR as intuitive and immersive, although they still considered face-to-face learning more supportive of collaboration. These findings suggest that usability shapes both immediate participation and longer-term acceptance. A VR system may contain strong educational content, but if learners struggle with control, navigation, or interaction logic, cognitive effort may shift away from learning and toward merely operating the environment. Thus, usability is not just a technical issue. It directly affects how efficiently learners can allocate attention to the intended academic task (Gervasi et al., 2023; Liu & Liu, 2025; Naz et al., 2024).

The studies also show that user experience in VR is strongly influenced by the quality of interaction design. Zöllner et al. (2025), for example, found that among several interaction variants for exploring nuclide charts in VR, the wall-controller model was the most preferred in terms of usability and user experience. This result is important because it demonstrates that even within the same content domain, not all interaction formats are equally effective. Langener et al. (2022) reached a similar conclusion in their work on embodiment illusion, showing that body control mattered more than avatar customization and that object manipulation produced the strongest experience of embodiment. These studies imply that user experience in VR depends heavily on whether learners can act naturally and purposefully within the environment. If interaction feels awkward, unrealistic, or cognitively demanding, the pedagogical value of the system may decline even when the content is relevant. By contrast, when controls are intuitive and actions map clearly onto learning goals, the virtual environment becomes a more convincing and supportive learning space. Therefore, user experience should be understood not as a superficial matter of comfort, but as an essential dimension of educational functionality (Langener et al., 2022; Zöllner et al., 2025).

This same pattern appears in development studies that emphasize validity and practicality as indicators of quality. Bancong and Nanda (2025) reported that their VR prototype for the photoelectric effect was strong in scientific accuracy, educational value, engagement, and visual quality. Mufit, Hendriyani, and Dhanil (2024) and Mufit, Dhanil, and Hendriyani (2025) likewise showed that immersive VR environments for quantum physics were rated highly in validity and practicality. Faqih et al. (2023) found strong evaluations from both experts and students in the development of the Fisikawaii Adventure platform. These results suggest that effective VR systems are usually those that combine sound content representation with usable and appealing interfaces. Importantly, practicality and expert validation in these studies function as more than technical approval. They indicate whether the instructional design is coherent enough to be used meaningfully in real educational settings. This reinforces the broader argument that the success of VR depends on how well design decisions translate disciplinary content into accessible and educationally relevant interaction forms (Bancong & Nanda, 2025; Faqih et al., 2023; Mufit, Dhanil, & Hendriyani, 2025; Mufit, Hendriyani, & Dhanil, 2024).

Across studies on serious games, science laboratories, mixed-reality learning, embodiment, and technical interfaces, the same conclusion appears repeatedly: VR is most educationally effective when learners can understand the task, navigate the environment comfortably, and interact with the system in ways that are directly tied to learning goals (Holly et al., 2021; Liu & Liu, 2025; Zöllner et al., 2025). This means that the educational debate should move beyond asking whether VR is innovative and instead examine whether it is instructionally coherent, usable, and supportive of meaningful learner action. The studies do not suggest that advanced technology alone guarantees strong learning. Rather, they show that good VR depends on good educational design. When usability is high, interactions are intuitive, and pedagogical structure is clear, VR becomes a powerful learning environment. When these qualities are weak, even immersive systems may fail to produce lasting educational value.

Implementation Challenges and Future Directions of VR in Education

Although the reviewed studies present VR as a promising educational approach, they also show that implementation remains constrained by a number of practical, pedagogical, and institutional challenges. One of the clearest patterns is that positive learning outcomes do not automatically translate into easy adoption. Abdullah et al. (2025), in their SWOT-based analysis, explicitly identified several recurring barriers, including high costs, motion sickness, infrastructure limitations, and educator hesitation. These issues are not peripheral. They directly affect whether VR can move beyond pilot projects and become part of regular teaching practice. A similar caution appears indirectly in other studies as well. Even when students respond positively to immersive environments, the transition from controlled experimentation to routine educational use still depends on technical readiness, institutional support, and user acceptance. Therefore, the literature suggests that the current debate should not focus only on whether VR can improve learning, but also on whether educational institutions are realistically prepared to adopt, maintain, and scale VR-based systems in diverse learning contexts (Abdullah et al., 2025).

A major implementation challenge concerns access to hardware, infrastructure, and technical support. Many of the reviewed studies were conducted in highly controlled settings with dedicated systems, specialized software, or purpose-built environments. For example, Li et al. (2021) developed a VR training platform for ITER-type mock-ups, Mantelli et al. (2023) created a VR environment integrated with dynamic models for steam generator training, and Mamodiya et al. (2025) designed a sophisticated cognitive digital twin framework for solar PV infrastructure. These studies demonstrate what VR can achieve, but they also imply substantial resource requirements. Systems of this kind depend on high-performance hardware, customized interfaces, and ongoing technical maintenance, all of which may be difficult to sustain in ordinary schools or under-resourced institutions. Even in less specialized educational settings, device availability, software compatibility, internet performance, and technical troubleshooting remain practical concerns. Thus, while the reviewed studies show that VR can function effectively in technical and educational environments, they also suggest that implementation at scale will remain uneven unless questions of affordability and infrastructure are addressed more directly (Li et al., 2021; Mamodiya et al., 2025; Mantelli et al., 2023).

Another challenge lies in human factors, especially usability, comfort, and educator readiness. Gervasi et al. (2023) found that students viewed VR and AR as intuitive and immersive, yet they still regarded face-to-face learning as more effective for collaboration. This indicates that technological acceptance does not eliminate pedagogical trade-offs. Similarly, Holly et al. (2021) argued that educational VR must balance user experience, ease of use, and pedagogical intent, which implies that poorly designed systems may burden rather than support learners. Langener et al. (2022) and Zöllner et al. (2025) also demonstrated that interaction design strongly affects the quality of user experience, suggesting that implementation problems may emerge when controls are unintuitive or physically awkward. These findings are important because they show that successful VR adoption depends not only on student interest, but also on whether users can engage comfortably and meaningfully with the environment. In addition, educator hesitation, as highlighted by Abdullah et al. (2025), remains a serious challenge. Teachers may be unsure about how to integrate VR into curriculum, assess its learning value, or manage technical issues during instruction. This means that implementation is partly a matter of professional development, not just technological procurement (Abdullah et al., 2025; Gervasi et al., 2023; Holly et al., 2021; Langener et al., 2022; Zöllner et al., 2025).

The reviewed studies also point to a methodological challenge that affects future implementation: the evidence base is positive, but not always equally strong. Hamilton et al. (2021) already noted that many immersive VR studies still contain weaknesses in experimental design and outcome measurement. This matters because institutions are more likely to invest in VR when the evidence is not only promising but also robust and comparable across contexts. Several reviewed studies provide strong indicators such as learning gains, effect sizes, validity scores, or usability outcomes, as seen in Mathew et al. (2025), Naz et al. (2024), Villada, Montoya, and Mendez (2026), and Maraza-Quispe and Palo-Rosas (2025). However, other studies focus more on feasibility, expert validation, or user perception than on long-term educational impact. This does not weaken their contribution, but it does suggest that the field still needs more consistent evidence about durability of learning, transfer across settings, and comparative advantage over non-VR methods. Without stronger longitudinal and comparative research, implementation decisions may continue to rely on short-term success indicators rather than on mature evidence of sustained educational value (Hamilton et al., 2021; Maraza-Quispe & Palo-Rosas, 2025; Mathew et al., 2025; Naz et al., 2024; Villada, Montoya, & Mendez, 2026).

In terms of future directions, the reviewed studies suggest that VR research is moving toward more specialized, intelligent, and interactive systems. The trajectory from 2021 to 2026 indicates a shift away from asking whether VR is broadly useful and toward identifying the conditions under which it is most pedagogically effective. This can be seen in the move from early reviews and exploratory studies toward advanced interfaces and domain-specific applications, such as sensory feedback gloves in medical training, wearable ultrasound-based interaction, cognitive digital twins, and mixed-reality systems that model continuance intention and user experience (Grandi et al., 2025; Liu & Liu, 2025; Mamodiya et al., 2025; Maraza-Quispe & Palo-Rosas, 2025). Another likely direction is the refinement of user-centered and iterative design, as shown in studies that improved systems through playtesting, expert validation, and repeated interface evaluation (Bancong & Nanda, 2025; Villada, Montoya, & Mendez, 2026). This suggests that the future of VR in education may depend less on generalized immersion and more on carefully tailored systems that combine instructional goals, responsive interaction, and user-specific design.

The literature suggests that the future of VR in education is promising but conditional. The reviewed studies do not support the claim that VR is ready to become a universal solution for teaching and learning. Instead, they show that its long-term contribution will depend on how well educational systems can address access, usability, teacher readiness, and evidence quality, while also continuing to develop more targeted and pedagogically coherent applications (Abdullah et al., 2025; Hamilton et al., 2021). Future research should therefore move in at least three directions: first, more rigorous studies that compare VR with other methods over longer periods; second, more attention to scalable and affordable implementation models; and third, stronger integration between pedagogical design and technological innovation. If these conditions are addressed, VR is likely to evolve from an innovative instructional option into a more stable and strategically valuable component of educational practice.

CONCLUSION

This thematic review shows that virtual reality (VR) has substantial potential to support physics learning, particularly in improving conceptual understanding, engagement, and learning experiences related to abstract and dynamic content. Across the 33 reviewed studies, VR was consistently associated with positive outcomes in areas such as conceptual gain, knowledge retention, motivation, and participation. The strongest evidence emerged in topics that are difficult to visualize through conventional instruction alone, including projectile motion, quantum physics, the photoelectric effect, electric fields, and virtual laboratory activities. However, the review also indicates that VR should not be treated as an inherently superior instructional solution in all contexts. Its contribution is strongest when the learning task genuinely benefits from simulation, visualization, and active conceptual interaction.

The review also highlights that the pedagogical value of VR is closely linked to immersion, embodiment, and interactivity. VR appears most effective when learners can engage meaningfully with content through bodily action, multisensory feedback, and well-structured virtual tasks. At the same time, the findings make clear that immersion alone is not sufficient. Without clear instructional design, intuitive usability, and a coherent alignment between interaction and learning goals, VR may remain at the level of novelty rather than producing deep conceptual learning. In this sense, the educational effectiveness of VR depends not only on technological sophistication, but also on the quality of design decisions that shape how learners experience and interpret the environment.

Another important conclusion is that VR is especially suitable for abstract, complex, and high-risk learning contexts, but its broader implementation remains conditional. The reviewed studies suggest that VR is highly promising for physics learning because it can make invisible processes more intelligible, create safe spaces for repeated practice, and connect theory with simulated experience. Nevertheless, recurring challenges such as cost, infrastructure readiness, usability, teacher preparedness, and uneven research quality continue to limit wider adoption. Therefore, VR should be understood not as a universal replacement for conventional instruction, but as a powerful and context-sensitive pedagogical approach whose effectiveness depends on appropriate content selection, instructional coherence, and realistic implementation conditions.

RECOMMENDATION

Based on the findings of this review, future work in VR for physics learning should move in three complementary directions. First, more rigorous and longitudinal studies are needed to examine not only immediate learning gains, but also retention, transfer, and sustained conceptual understanding over time. Second, future development efforts should prioritize instructional design, usability, and learner-centered interaction rather than focusing solely on immersive features. Third, implementation research should pay greater attention to scalable and affordable models that can be adapted to real educational settings, particularly in contexts with limited infrastructure. For educators and developers, this means that VR should be integrated selectively into physics instruction, especially for topics that are abstract, dynamic, or difficult to reproduce safely in conventional classrooms.

ACKNOWLEDGEMENT

The author would like to express sincere appreciation to all researchers whose studies contributed to this thematic review. Their work provided the empirical and conceptual foundation for understanding the pedagogical potential, limitations, and future directions of virtual reality in physics learning.

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