Received: 31 October 2024 | Revised: 18 December 2024 | Accepted: 14 February 2025 | Published online: 5 March 2025

RESEARCH ARTICLE

International Journal of Changes in Education
2025, Vol. 2(3) 152–161
DOI: 10.47852/bonviewIJCE52024697

BON VIEW PUBLISHING

From Abstract Concepts to Engaged Learning: An IVR Game-Based Framework for Physics Education

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Abstract: Physics education often faces challenges in communicating abstract concepts effectively and maintaining student interest. This study explored the integration of immersive virtual reality (IVR) with game-based learning to improve educational impact and student engagement. The designed IVR game included the principles of inquiry-based, constructivist, and situated learning. It included four levels that mimicked real-world physics situations, each focusing on a particular physics concept and featuring interactive puzzles. This setup enabled students to progress throughout the game while improving their understanding of abstract concepts. The addition of characters such as guides and opponents enriched the storyline and elevated the immersive experience. The experimental results of 19 participants from four different majors demonstrated positive gaming experiences and an improved understanding of the physics concepts. Most of the participants rated the physics education game highly for its positive impact and participation, showing a significant interest in learning through the IVR platform. In general, 95% of the participants gave the game high ratings for its educational value and overall learning experience. The study highlighted the promise of game-based IVR learning in the advancement of physics education and highlighted ways to increase student motivation and participation.

Keywords: higher education, virtual reality, game-based learning, student engagement

1. Introduction

Teaching and learning physics has proven to be a difficult task for educators and students, mainly due to the fundamentally abstract nature of many concepts within the discipline [1]. Traditional teaching approaches could often lack the level of interactivity necessary to effectively engage students and teachers [2]. This limitation highlighted the need to identify innovative ways to help engineering students understand physics more effectively and apply the knowledge to solve real-world problems. Furthermore, low student engagement in learning physics was often caused by outdated educational settings. The demands to reexamining the content of physics education focused on the diversification of the skills of students, created more equitable learning spaces, and prepared students to address significant social challenges [3].

Various approaches have been proposed to address these issues, with game-based learning (GBL) emerging as a promising avenue [4, 5]. Educational games came in many forms, covering a wide array of platforms and devices, from online computer games to mobile applications [6]. The genres were diverse, including simulations, role-playing games, puzzles, sports-themed games, and even those that blended multiple genres [7]. Many studies used both quantitative and qualitative methods to analyze educational games at different educational levels, from early kindergarten to higher education. These studies showed that educational games were increasing academic interest and real-world applicability.

Research has indicated that educational virtual reality (VR) games hold promise in educational settings, demonstrating their utility at various academic levels and beyond the classroom, especially in healthcare education [8]. However, many physics-oriented educational games still use two-dimensional or flat tabletop formats, limiting the immersive qualities that virtual reality can offer. This approach provided an opportunity for further exploration of VR as a method of enhancing physics learning [9]. VR created the possibility for highly immersive and interactive educational settings, allowing students to understand physics concepts through engaging, story-driven gameplay.

Some studies have shown that gamified VR has shown promise as a powerful educational tool that can enhance learning across a broad spectrum of subjects and educational stages [10]. For example, Korlat et al. [11] develop PhyLab, a VR-based laboratory designed to test the effectiveness of a game-based VR teaching approach on secondary school students' self-confidence, interest, and performance in physics. The results indicated that the game-based VR method improved student performance and increased their motivation to study physics during the critical teen years. Furthermore, Zhurakovskaia et al. [12] compare a browser-based 2D application with a VR 3D immersive game to examine the effectiveness of immersive games for teaching. The findings showed that the VR-based game allowed most

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students to identify the mistakes in their studies and learn from the mistakes, suggesting that this approach led to a better understanding of the abstract knowledge of physics.

Research into extended reality methods in education has expanded beyond VR to include augmented reality (AR), which has shown promise in motivating students to learn physics. Zafeiropoulou et al. [13] investigate the use of AR in a treasure hunt game designed for fifth-grade students in a Greek primary school. By integrating AR game-based learning (ARGBL) into the curriculum, students could interact with digital content and manipulate virtual objects during physics experiments. Feedback from teachers and students was overwhelmingly positive, suggesting that ARGBL could be an effective educational tool. It not only facilitates teaching physics but also increases student engagement and motivation. Another study by Vidak et al. [14] dives into the technical aspects of AR in physics education. Their analysis covered a range of topics, including various content areas in physics, the educational level of the participants, sample sizes, and different research methodologies. The findings indicated that AR could improve both learning motivation and educational outcomes in physics classes. However, research conducted by Czok et al. [15] reveal that although AR environments often entailed higher cognitive demands, this did not necessarily result in lower knowledge acquisition compared to traditional learning settings. Furthermore, despite the use of game-based educational environments, AR did not lead to better learning outcomes in the specific context of the subject matter and audience of their study.

Neroni et al. [16] explore the potential of VR games in design cognition research that highlighted the usefulness of VR games for ideation, prototyping, problem reframing, and intrinsic motivation. These applications involved various design-related activities, including on-screen tasks, verbal communication, physical gestures, digital models, and test results. The findings suggested that VR games can play a key role in training interventions for design education and professional practice. Lin and Chang [17] evaluate the impact of VR science education games on learning efficiency through the integration of embodied cognition. Their results demonstrated moderate positive effects on learning, significant skill training, improved interaction, and improved knowledge learning in various disciplines. To guide the development of VR science education games, the study proposed a five-phase human–computer interaction design strategy focused on virtual scenes, embodied schemas, body projection, behavioral input, and learning outcomes. Iquira et al. [18] examine the influence of VR and gamification on physics learning within mobile learning environments. Their work focused on providing low-cost alternatives to distance learning, particularly for institutions that lack the infrastructure to create physical physics laboratories. The results indicated that mobile VR environments could be highly suitable for distance learning in physics, offering an effective and scalable solution.

Meanwhile, Zeng et al. [19] investigate the design of VR games in physics education, emphasizing the importance of incorporating guides into GBL to improve student learning experiences. By integrating these elements, educators can improve engagement and ensure that learners receive clear guidance throughout the educational process. Ervin et al. [20] introduce a data-driven hydrodynamic VR simulation experience that provides a unique perspective for navigation scientists. This simulation allowed scientists to better understand how coastal waves affect landing operations and channel design. Using FUNWAVE data generated from supercomputer resources, the study emphasized the importance of visualizing graphical representations when delivering complex abstract concepts, such as those in physics.

In general, physics education often presents challenges due to abstract concepts, inappropriate teaching methods, and low student engagement. To address these issues, this study explored the integration of VR with GBL to create an immersive and interactive learning environment. The aim was to improve student motivation and engagement while reducing the burden on educators tasked with teaching physics. The study made several key contributions:

1) Explored the impact of immersive VR (IVR) with a science fiction narrative in improving the engagement of students in learning physics concepts through interactive gameplay.
2) Investigated the design methods of game elements with visualization techniques to improve the student's understanding of abstract physics concepts.
3) Developed scenarios that transition students from basic knowledge acquisition to problem-solving application, where they utilized the physics concepts they learned at each level to overcome the final challenges for winning the game.

2. Research Methodology

The overall design framework for the proposed IVR game-based physics education is illustrated in Figure 1. This framework demonstrated the integration of physics knowledge into IVR games to enhance both entertainment and educational experiences. The game, developed using Unity3D, operated on the Meta Quest 3 headset.

2.1. Game design goals and learning philosophies

Game design aimed to create a comprehensive educational ecosystem by integrating principles of inquiry-based, constructivist, and situated learning [21]. Inquiry-based learning promoted self-directed exploration and hands-on tasks, prompting players to pose questions, discover answers, and engage in self-reflection. Constructivist learning principles facilitated the construction of personalized knowledge as players manipulated and experimented with physical principles within the virtual environment. Situated learning emphasized the practical application of knowledge and skills within specific contexts, with each level simulating real-world problem-solving scenarios.

Furthermore, the design of games drew inspiration from Schrier [22], supporting the use of games as a medium to convey moral thinking and values. Within this game, the players have completed physics-related puzzles, using scientific knowledge to defend their station against aliens. This experience was designed to shape the moral values of the players, fostering an appreciation for knowledge and the importance of accountability. The game adopted a task-driven learning cycle in which, prior to each level, a virtual scientist assigned a task to the player, providing theoretical insight into the relevant physics principles. This phase served as the learning stage, allowing players to understand the concepts. Subsequently, players entered the application phase, applying these principles directly within the level to solidify their understanding through practice. The successful completion of a level depended on the precision of solving the presented puzzles, serving as comprehension and practical application tests, thus constituting the ”learn,” ”apply,” and ”test” cycle, as depicted in Figure 2.

2.2. Game components module

The module of components of the game included the background story (narrative), level mechanism, characters (guide), interaction, and artistic feedback.

2.2.1. Background story

The proposed IVR game was designed to provide guidance for students to learn theoretical physics content through gaming [23]. It

Figure 1
Overview of the design framework for IVR game-based physics education

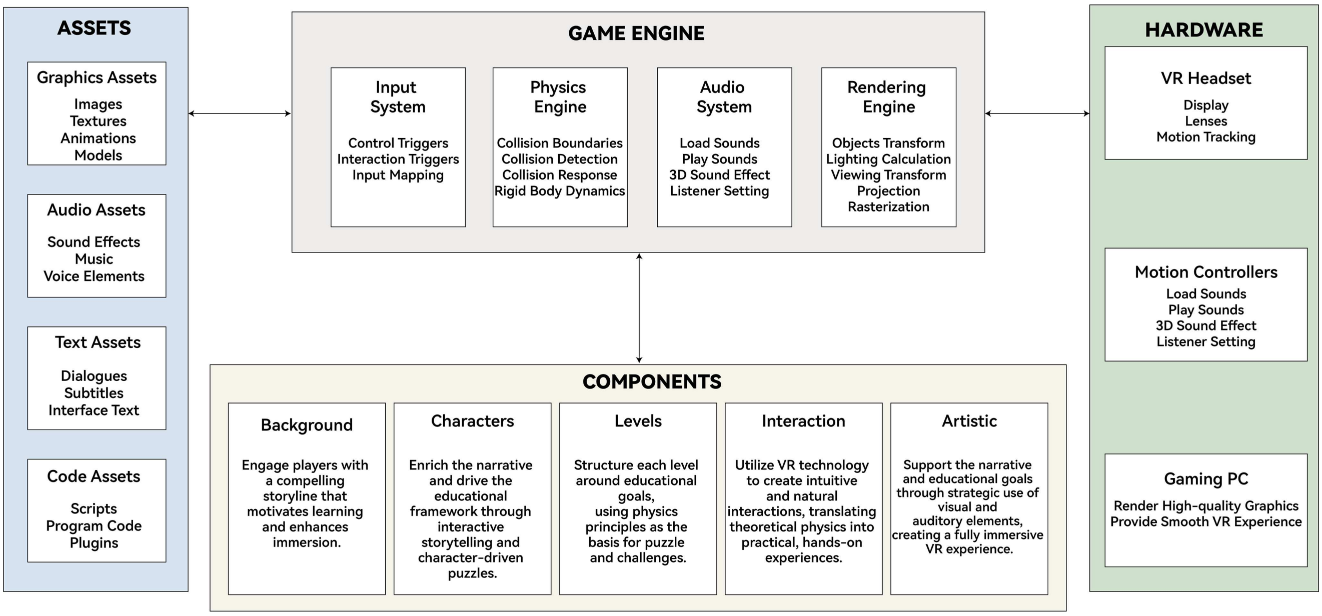
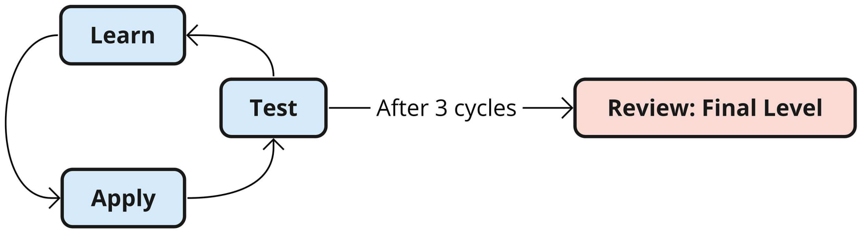


Figure 2
Overview of task-driven learning cycle



employed digital storytelling methods to create a compelling narrative, integrating elements of sci-fi galaxy fiction. This approach was designed to increase user engagement and motivation. The game was created as an educational tool in addition to entertainment. It sought to integrate enjoyment with learning, allowing students to immerse themselves in the storyline of the game while simultaneously deepening their understanding and application of the principles of physics. The background story for the game design was as follows:

> *"Humanity's expansion into the cosmos leads to the establishment of grand space stations that symbolize progress and civilization. Among these stations is 'Guardian Star,' which encounters an unprecedented crisis: aliens infiltrate the station with the intent of seizing control of its defensive system, thus allowing the intrusion of their army. As the defensive system falls under alien control, a loyal guard, remotely guided by a scientist, was sent on a mission to regain control. To achieve this objective, the guard must navigate through various physics-based puzzles to unlock access to the control room of the defensive system. Additionally, the guard must challenge and defeat aliens to protect the station."*

2.2.2. Level mechanism

The game design contained four levels, each featuring a different puzzle that the students must win sequentially. Figure 3(a) provides an overview of these levels. Table 1 details the mechanisms associated with each level, including the physics principles, mechanics of the game, and outcomes. The game integrated vari-

Table 1
Overview of the mechanisms associated with each level, detailing the integration of physics principles, gaming mechanics, and outcomes

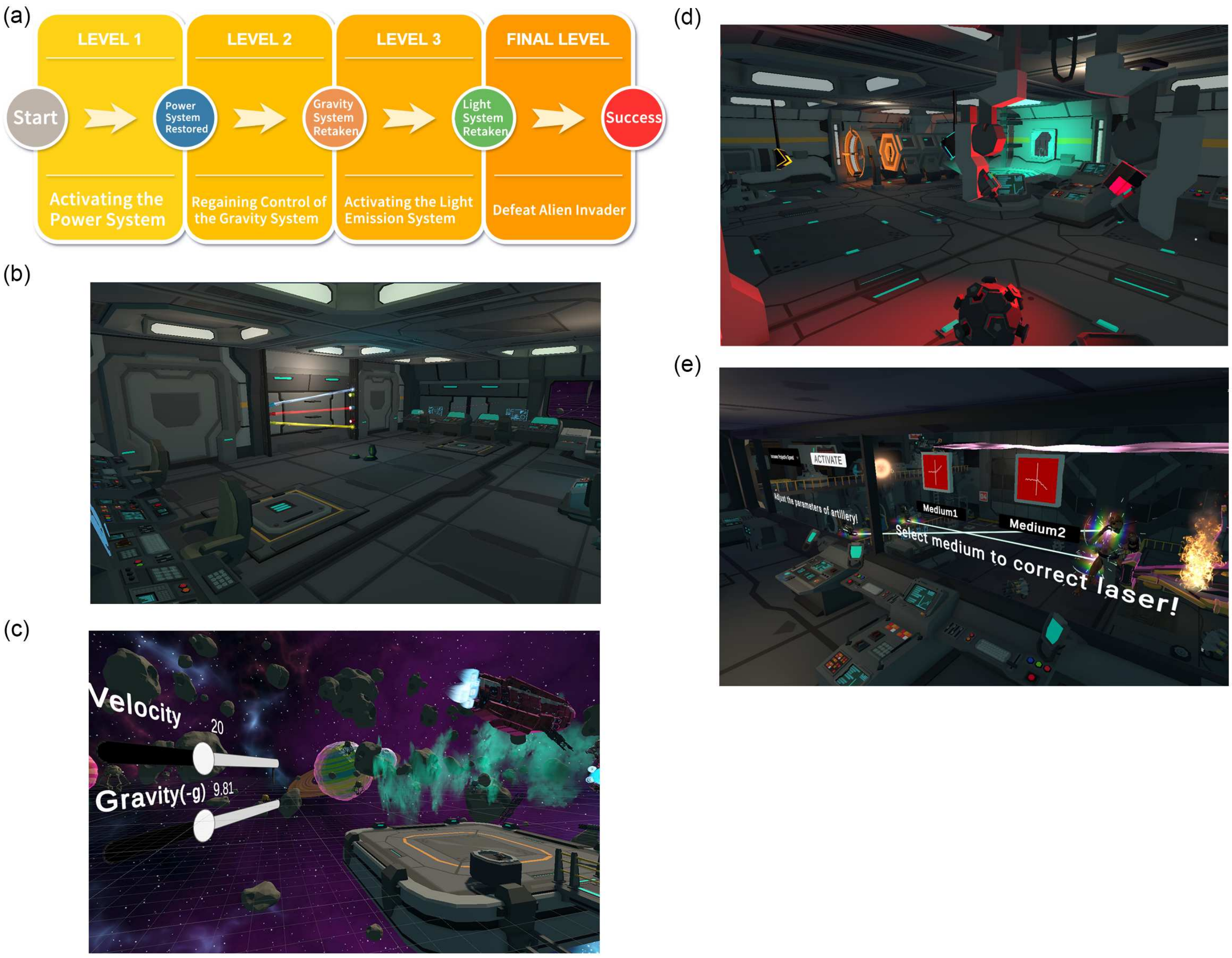
Level	Concept	Objective	Description	Outcome
1	Light refraction	Visualizing light refraction under different mediums	Three different colored emitters and receivers were presented, and students had to observe the effects of light under different mediums, placing the correct medium on each light patch of each light ray and then adjusting the light path orientation to achieve refraction to the correct receivers (see Figure 3(b)).	Restoration of the power system allowed access to the room with the gravity system

(*Continued*)

Table 1
(*Continued*)

Level	Concept	Objective	Description	Outcome
2	Gravity and projectile motion	Understanding parabolas and gravity by adjusting speed and gravitational force	Students were tasked with eliminating flying robots appearing at different distances by adjusting the gravitational force and speed parameters of the weapon so that the ray could accurately shoot at those robots (see Figure 3(c)).	Regained control of the gravity system
3	Light propagation	Understanding light travel paths and patterns through shadow observation	Students were tasked with adjusting the light emission travel path to align with the shadows shown on the wall (see Figure 3(d)).	Restoration of the light emission system subsequently reactivated the weapon defensive system
4	Application of the above concepts	Applying concepts learned at prior levels (assessment of learning outcome)	Students were tasked with adjusting the parameters of two heavy weapons, utilizing physics concepts learned in the prior levels so that the weapons could hit the alien accurately (see Figure 3(e)).	Won the game

Figure 3
Overview of the (a) four different-level mechanisms with different goals, including screenshots of scenarios in (b) power system, (c) gravity system, (d) light emission system, and (e) encountered with alien, all of which require knowledge of physics to succeed



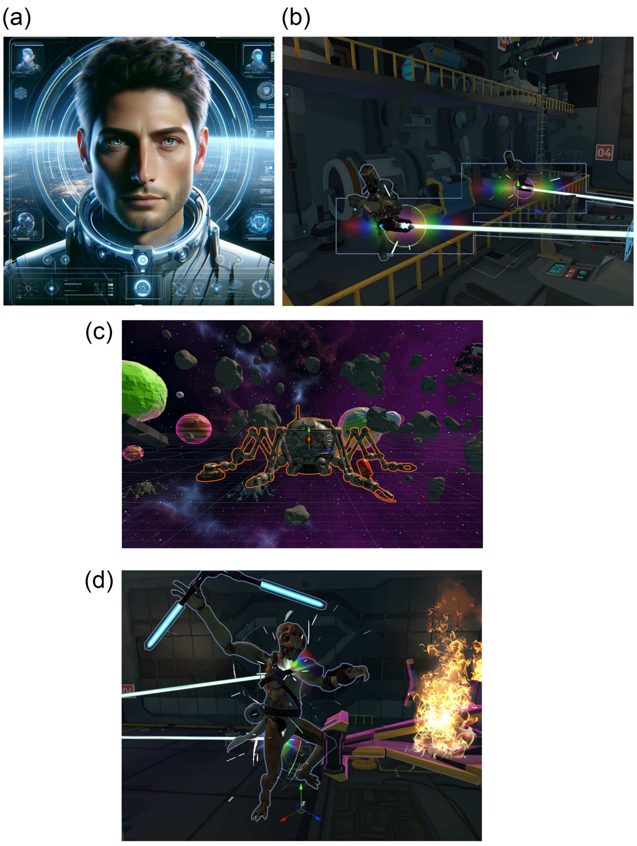
ous physics concepts, including light refraction, gravity, projectile motion, and light propagation, all visualized within the game environment.

2.2.3. Characters

In the proposed IVR game, the characters served to enrich the narrative and advance educational objectives [24]. The game featured two primary character types, which were the player characters and non-player characters (NPCs).

Controlled by a user, the loyal guard navigated various rooms to solve physics-based puzzles. In addition, four NPCs were integrated into the design of the IVR game. Dr. Nova, a virtual scientist, acted as a guide, providing hints or clues by delivering physics-related knowledge, directing students to specified locations, and stating game objectives through audio communication (see Figure 4(a)). The students controlled heavy weapons (see Figure 4(b)) to combat aliens (see Figure 4(d)). Lastly, robots (see Figure 4(c)) were enemies that could manipulate gravitational fields, which required the guard to defeat these robots to restore the gravity system.

Figure 4
Design of the characters, including (a) guide (Dr. Nova, protagonist), (b) heavy weapons (protagonist), (c) gravity-control robot (antagonist), and (d) alien (antagonist)



2.2.4. Interaction

In IVR games, interaction design served as the foundation of the immersive experience, allowing the connection between students and the world of the game. Through well-designed interactions, students could interact with the game environment in an intuitive way, thus enhancing both its educational and entertainment experiences. The proposed IVR game integrated four different methods for object interaction, improving the immersive experience for students. Table 2 provides an overview of the object interaction modes integrated into the proposed IVR game.

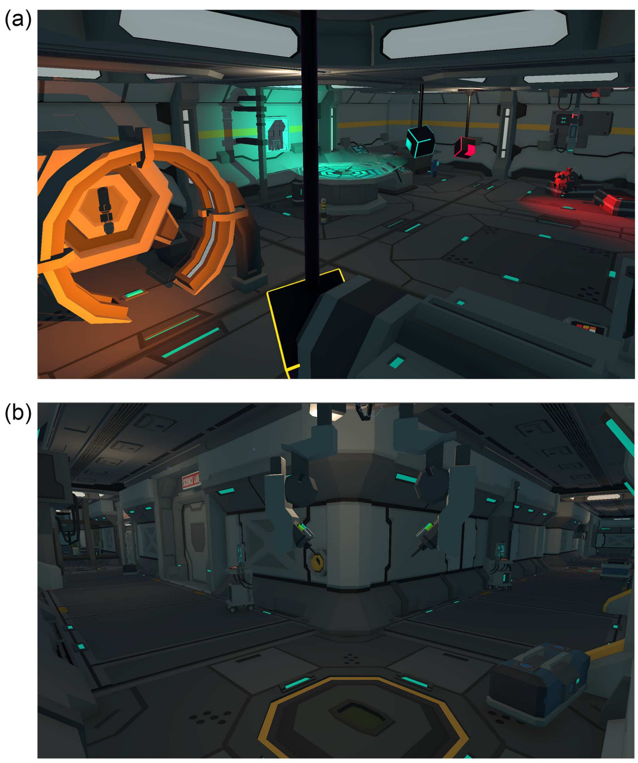
Table 2
Implemented object interaction modes in the IVR game

Mode	Description
Grab	Enabled the manipulation of virtual objects to solve puzzles
Activate	Triggered actions, such as firing a weapon
Select	Function as to clicking a button
Drag	Enabled interaction with slider for puzzle-solving

2.2.5. Artistic feedback

To increase the immersive experience, the integration of music and sound effects aimed to cultivate the atmosphere of cosmic space stations, promoting a sense of realism and futurism for students. Through this approach, the students found themselves enclosed within a space station environment that reflected both modern and futuristic esthetics. Moreover, visual cues in the form of colors were employed as guides throughout the game. For example, red denotes a disconnected mode, while blue indicates a connected (solved) mode, as illustrated in Figure 5(a).

Figure 5
Artistic feedback design that showcases (a) color implementation and (b) simplified space structure layout



The layout of routes leading to different rooms, essential for puzzle-solving, was intentionally simplified. This design choice was made to reduce the potential motion sickness and discomfort that arise from complex station layouts, which could introduce obstruc-

Table 3
Participants' information

Faculty	Major	Number of participants	Experienced in VR
Faculty of Science and Engineering	Computer Science	14	Yes
	Computer Science with Artificial Intelligence	2	Yes
Business School	Finance and Accounting	2	No
Humanities and Social Science	Economics	2	No

tions to students' ability to navigate efficiently. By rationalizing the routes, students could concentrate more easily on both the game and educational components, minimizing navigational challenges (see Figure 5(b)).

2.2.6. Expands on previous study

This study builds upon previous research by incorporating engaging storylines into the physics education content to improve student engagement. Although previous studies primarily emphasized educational content design, this work goes a step further by integrating elements of game design such as real-time feedback, guide characters, and structured level mechanisms. These features were strategically included to create a more immersive and interactive learning experience for participants, bridging the gap between educational objectives and GBL principles.

To ensure the reproducibility and transparency of the study, the research team is committed to making the data available upon request. This approach aims to support further academic inquiry while ensuring that data are used ethically and responsibly, according to established research guidelines and protocols.

2.3. Experiment design

Experiments were conducted to assess both the effectiveness of the proposed IVR game and its educational value, as well as to evaluate the overall gaming experiences of the students. Participants were recruited through an interest call in student community groups on a social media platform. The recruitment was aimed at undergraduates from diverse disciplines. The inclusion criteria required the willingness to participate in the educational VR experiment. The excluded criteria included susceptibility to motion sickness, severe visual impairments, or conditions that could compromise the safety of the participants.

A total of 19 participants, with a mean age of 22.5 years, were recruited from the campus, comprising 16 students majoring in computer science and three students from other majors. Among the participants, 11 had little to no VR gaming experience, five had some experience, and three were active VR gamers. Table 3 provides a summary of the information from the participants. Upon instruction on the objectives of the experiment, participants were asked to sign a consent form if they agreed to proceed. Subsequently, participants engaged in the gameplay using the VR headset, with the assurance that they could withdraw at any time if discomfort occurred. Each participant was briefed by the researcher with a 5-min overview of the experiment task, which was then followed by 25 min of gameplay.

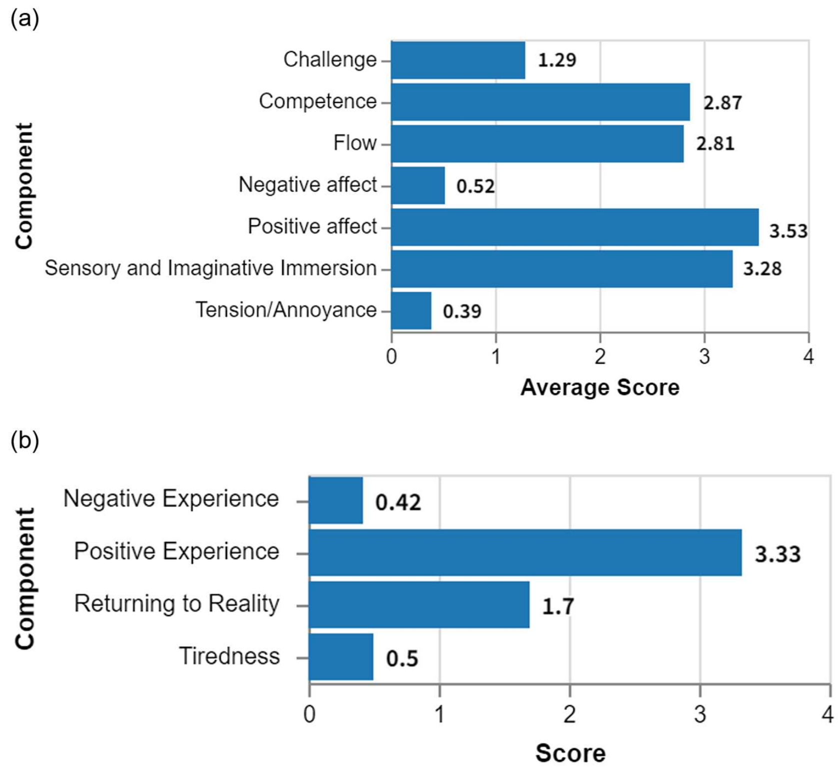
At the end of the experiments, participants were asked to fill out two questionnaires to collect feedback for about 10 min. These questionnaires included the Game Experience Questionnaire (GEQ) [25] and a self-designed Learning Assessment Questionnaire (LAQ). The GEQ was designed to offer a complete understanding of the player's gaming experiences by evaluating various aspects such as sensation, emotion, fluency, excitement, and challenge. Since the proposed game was a single-player VR experience without cooperative or competitive gaming components, questions related to social interactions were omitted. Consequently, the GEQ focused on the core module and the GEQ post-game module, both of which were rated on a 5-point Likert scale.

The self-designed LAQ was created to assess the efficacy of the game in improving player comprehension and skill development and promoting interest in learning. Comprising five questions (see Table 4), the LAQ sought to gather feedback on the educational influence of the game from the student's point of view, while also pinpointing the strengths and weaknesses of the game in knowledge learning.

Table 4
Self-design LAQ

No	Question	Type
Q1	After playing the game, how well do you understand the concepts it presents?	5-point Likert scale (5P-LS): 0 (not understand) to 4 (completely understand)
Q2	To what extent has the game stimulated your interest in physics?	5P-LS: 0 (not inspired) to 4 (highly inspired)
Q3	Do you find the educational content of the game suitable for your needs?	5P-LS: 0 (not appropriate) to 4 (highly appropriate)
Q4	How would you rate the game in general?	5P-LS: 0 (very poor) to 4 (excellent)
Q5	Do you have any suggestions or comments that you would like to share with us?	Text-based (optional)

Figure 6
GEQ scores for (a) core module and (b) post-game module



3. Results and Discussion

3.1. GEQ findings

The general findings suggest a favorable acceptance of the game, as illustrated in Figure 6(a) and (b) for the core and post-game modules, respectively.

In the core module, a score of 3.28 for the sensory and imaginative immersion component indicated deep participation of the participants within the game. The positive emotion component scored 3.53, while the negative affect component scored 0.52, indicating the ability of the game to evoke positive emotions in participants. The smooth experience component, with a score of 2.81, highlighted the effectiveness of game design in maintaining the attention of the participants. However, scores for the challenges and sense of competence components were relatively low at 1.29 and 2.87, respectively, suggesting areas for improvement in difficulty and the sense of achievement of the participants. In particular, the tension or annoyance components scored only 0.39, indicating a generally relaxed or pleasant emotional state among participants during the game.

In the post-game module, a score of 3.33 for the positive experience component suggested sustained positive emotions among participants after the game. Furthermore, scores of 1.7 for the return to reality component and 0.5 for the tiredness component indicated the participants' ability to quickly adjust to the virtual environment of the game without feeling overly fatigued.

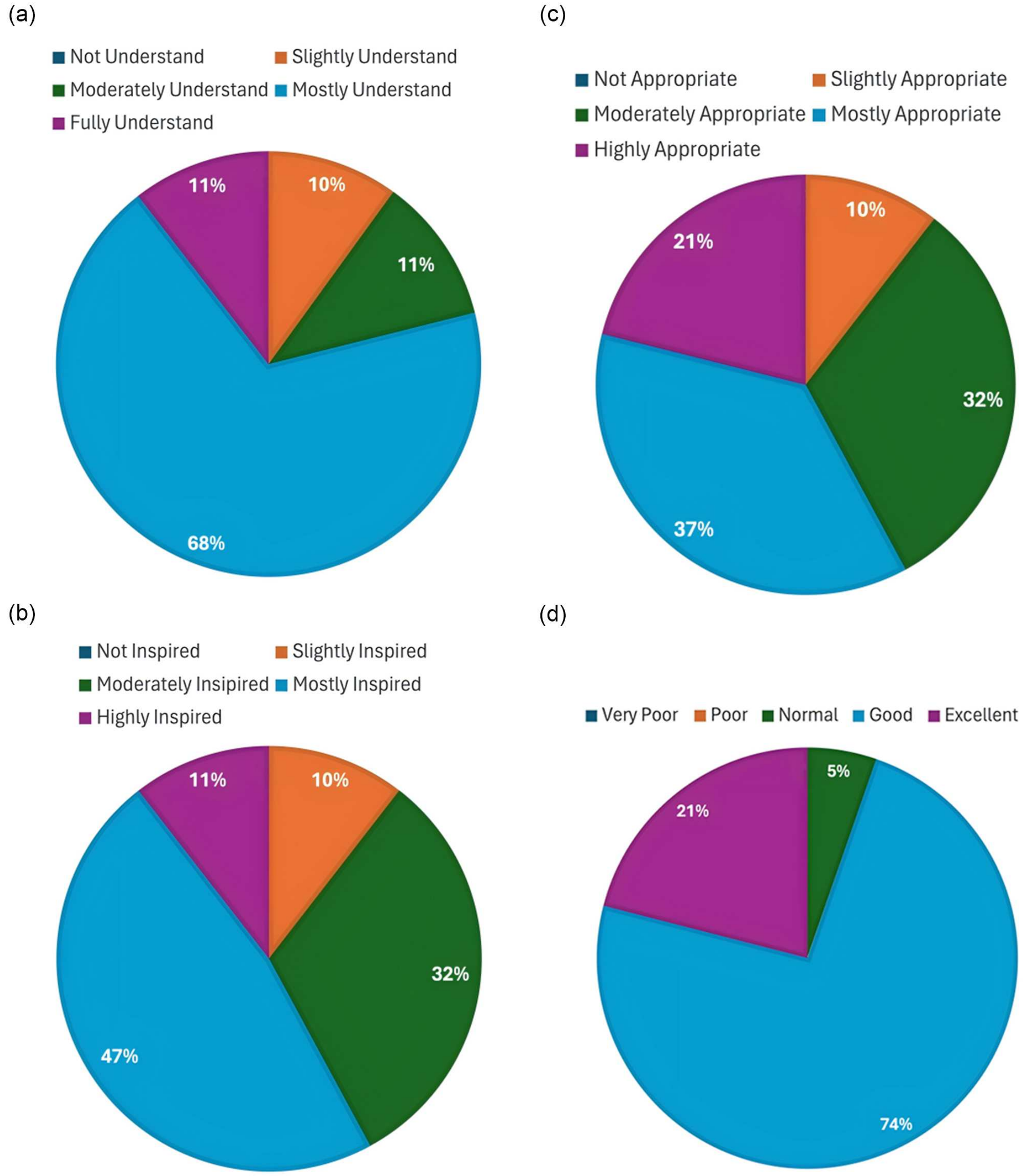
3.2. LAQ findings

The LAQ findings primarily reflect the evaluation of the proposed IVR game from the participants. The results of the statistical analysis are summarized in Figure 7.

The ratings indicated agreement among the participants on the effectiveness of the proposed IVR game in conveying abstract physics knowledge through GBL, and 79% of the participants (see Figure 7(a)) reported a good understanding of the physics content (68% mostly understand, 11% fully understand). Furthermore, more than half of the participants indicated that the game increased their interest in learning (see Figure 7(b)), with 11% highly inspired and 47% mostly inspired. This underscored the potential of the IVR game to stimulate physics learning. Similarly, more than half of the participants (58%, see Figure 7(c)) found the physics contents designed as a game appropriate for their learning, with 37% mostly appropriate and 21% highly appropriate. The overall rating of the proposed IVR game was exceptional, with 95% rated as good or excellent (see Figure 7(d)).

Table 5 presents the feedback received on the suggestions and comments on the proposed IVR game. In general, the results indicated that the game effectively conveyed abstract physics knowledge to some extent and contributed to enhancing learning motivation. However, several participants offered constructive suggestions for improvement. Two comments (no. 8 and no. 9) indicated insignificance in game design with respect to knowledge of physics. In contrast, three comments (no. 1, no. 3, and no. 10) suggested enhancing the guidance element within the game, beginning with the introduction of relevant physics teaching before engaging in the game. Some participants expressed interest in replaying the game for educational purposes, while others recommended increasing the difficulty and content of the game. Specifically, one participant suggested refining the viewpoint for an improved gaming experience (no. 12). Despite this, the proposed IVR game significantly captured the attention and interest of most participants, showing evocative promise in facilitating physics learning.

Figure 7
LAQ scores and feedback corresponding to (a) understanding of the concept of physics (Q1), (b) interest in learning (Q2), (c) appropriateness of the contents of physics (Q3), and (d) overall rating (Q4) as depicted in Table 4



3.3. Practical implications, limitations, and future work

3.3.1. Practical implications

This study highlights the potential of IVR games in revolutionizing physics education. By integrating GBL principles with advanced visualization techniques, the proposed IVR game successfully bridges the gap between abstract physics concepts and real-world applications. The findings suggest that this approach can improve student motivation, engagement, and understanding of complex physics topics. In addition, the study presents a scalable model for adaptation in other STEAM fields, equipping educators with tools for active inquiry-based learning. Institutions can implement similar IVR frameworks to improve self-directed exploration and understanding, and policymakers can use these insights to invest in technologies for educational reform. This IVR model also has applications in professional training, where physics is essential, such as in engineering, aviation, and medical physics.

3.3.2. Limitations

First, most of the participants were computer science students, possibly skewing results toward technological familiarity and acceptance of IVR learning, limiting generalizability to nontechnical students. Second, the small number of participants (19) restricts statistical results and may not capture diverse learning experiences. Third, external factors such as previous physical or gaming

Table 5
Feedback from participants

No	Comments or suggestions
1	More guiding information is needed; the game incorporates a lot of physics, but additional teaching would improve it.
2	Consider including more meaningful content in the game.
3	Add clearer visual demonstrations or explanations.
4	The level of educational intensity is insufficient.
5	I was impressed by this game. At each step, critical thinking is required to determine how to progress through the scene and pass each level. Furthermore, the game continually encourages me to analyze its logic.
6	I think it could be slightly more challenging.
7	I really like it so much; I consider this game to be excellent.
8	I feel like I cannot fully connect physics to this game.
9	I think more basic information should be covered.
10	Consider improving the route guidance elements to make them more obvious within the game scene.
11	I still want to play another round with new content.
12	Perhaps the camera movement could be improved.
13	Overall, it is good.

experience, which could influence outcomes, were not explored in detail. Furthermore, while ethics were considered, clearer variable controls and recruitment criteria would increase replicability. Lastly, despite aligning the gameplay with educational goals, some participants indicated that the integration of physics principles and the gameplay could be refined.

3.3.3. Future work

Future work should focus on several key areas. First, increasing the pool of participants to more than 100 individuals from different academic backgrounds will provide a more comprehensive evaluation of the effectiveness of the game between disciplines. Second, the integration of dynamic difficulty adjustment mechanisms and reward systems could provide a wider range of learning abilities and improve engagement. Third, additional work should investigate the long-term impact of IVR-based learning on knowledge retention and transfer to real-world applications. Future iterations of the game should also include more detailed guidance and visual demonstrations to reinforce physics concepts and reduce cognitive load. Finally, making the dataset and the game design framework publicly accessible (with ethical safeguards) would allow other researchers to replicate, validate, and extend the study findings, contributing to the broader adoption of IVR technologies in education.

4. Conclusion

The study investigated the fusion of IVR technology with GBL to augment physics education, with a focus on addressing common challenges encountered in teaching physics, such as abstract concepts, inadequate teaching methodologies, and low student engagement. The methodologies described the design framework for the proposed game-based IVR approach to physics education, emphasizing the creation of an interactive learning environment advantageous for self-directed exploration, personalized knowledge construction, and practical application of physics principles. The GEQ and LAQ findings indicated that the participants generally accepted the game favorably. Specifically, participants demonstrated a strong understanding of physics concepts, increased interest in learning, and overall positive experiences with the game. However, one limitation identified was a potential bias toward understanding the educational aspects of the physics principles presented in the game. Future work aimed to collaborate with relevant physics educators in the design and evaluation of the game to enhance overall gaming experiences. In addition, future studies will focus on the enhancement of student engagement and learning outcomes in physics education through interactive serious game design methods.

Acknowledgement

The authors are grateful to the faculty office at the University of Nottingham Ningbo China for the assistance in participant recruitment.

Funding Support

This work was supported in part by the Faculty of Sciences and Engineering under grant I01240900001 and in part by the UNNC Education Foundation through Li Dak Sum Innovation Fellowship under grant LDS202307.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

The data that support the findings of this study are available upon reasonable request to the corresponding author.

Author Contribution Statement

Ying Zhang: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft. **Ruiqi Zhang:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – review & editing, Visualization. **Boon Giin Lee:** Conceptualization, Validation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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How to Cite: Zhang, Y., Zhang, R., & Lee, B. G. (2025). From Abstract Concepts to Engaged Learning: An IVR Game-Based Framework for Physics Education. *International Journal of Changes in Education*, *2*(3), 152–161. https://doi.org/10.47852/bonviewIJCE52024697