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Designing and validating a virtual reality prototype for photoelectric effect experiments

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Abstract

The photoelectric effect, which reveals the emission of electrons from material when exposed to light, is a foundational experiment in quantum physics that elucidates the interaction between light and matter. However, the lack of laboratory equipment and the difficulty of the experiment frequently prevent its conduct in educational settings. To address these challenges, this study developed and validated a virtual reality (VR) prototype designed to simulate the photoelectric effect experiment. The VR tool enables students to manipulate key variables such as light frequency and intensity, observe electron emission, and investigate the responses of various metals in real-time. The study adopted a research and development methodology, which involved iterative design, development, and validation by a panel of experts. The prototype was assessed on criteria including accuracy, educational value, and usability. The results indicate that the VR prototype accurately simulates the photoelectric effect. Validation data confirmed the educational effectiveness of the tool, which received high ratings for engagement and visual quality. While VR offers a flexible, scalable, and safe environment for exploring complex quantum phenomena, it is positioned as a complementary tool to enhance, rather than replace, traditional laboratory experiences. This approach is particularly valuable for institutions and high schools where expensive equipment may not be available. Future work will focus on expanding the scope of the VR tool to cover additional quantum experiments and improving user comfort to ensure broader accessibility for diverse educational settings.

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1. Introduction

Experiments are fundamental to the field of physics, serving as a bridge between theoretical concepts and practical applications [1, 2]. Through experimentation, students can observe physical phenomena directly and test and validate scientific principles [3, 4]. Experimentation can also strengthen students' understanding of theoretical knowledge and develop critical thinking and problem-solving skills that are integral to the scientific inquiry process [5, 6]. By participating in the scientific method, students gain experience in formulating hypotheses, designing experiments, collecting and analysing data, and drawing meaningful conclusions [2, 7, 8]. Beyond educational purposes, experiments are critical for advancing the field of physics, as they provide empirical evidence to support or challenge existing theories [1].

Despite the critical role of experimentation in physics education, there are significant challenges in conducting experiments, particularly those involving complex quantum phenomena such as the photoelectric effect [9–11]. The photoelectric effect, which illustrates the emission of electrons from a material when exposed to light, is a foundational experiment in quantum mechanics [12, 13]. This experiment is crucial for understanding the dual nature of light and the quantisation of energy, yet it can be difficult to teach using conventional classroom resources. Traditional methods often fall short of effectively engaging students and conveying the complexity of the phenomena, largely due to limited laboratory equipment and the abstract nature of quantum concepts [9–11].

In recent years, innovative technologies like virtual reality (VR) have emerged as powerful tools for addressing the limitations of traditional physics education. VR offers immersive and interactive environments that allow students to explore scientific phenomena more engaging and experientially [14, 15]. While VR is not intended to replace real-world experiments, it serves as a practical alternative for settings where traditional laboratory equipment is unavailable. By creating virtual laboratories, VR enables students to conduct experiments that would otherwise be difficult, expensive, or even dangerous to perform in a physical setting [16–18]. For example, VR simulations of the photoelectric effect allow students to manipulate variables such as light intensity and frequency, observe the resulting electron emissions, and measure the energy of emitted electrons. This hands-on interaction with the experiment facilitates a deeper understanding of key quantum mechanics concepts such as energy quantisation and the threshold for electron emission [13, 19].

Moreover, VR technology provides a platform for visualising abstract concepts and conducting thought experiments that are central to the study of physics [18]. Through immersive simulations, students can explore the quantum phenomena that are challenging to conceptualise using traditional teaching methods [20]. By engaging with these simulations, students are not only able to visualise complex ideas but also to experiment with them in a virtual space, thereby reinforcing their understanding through active participation and experimentation [17]. In addition to enhancing conceptual understanding, VR technology has been shown to improve students' engagement and motivation in physics courses. Studies have demonstrated that students who participate in VR-based learning activities are more likely to develop a deeper interest in the subject matter, as the immersive nature of VR fosters curiosity and a sense of discovery [21]. This increased engagement is particularly important in the context of teaching complex topics like the photoelectric effect, where traditional instructional methods may struggle to capture students' attention or convey the intricacies of the phenomena.

While the benefits of VR in physics education are well-documented, there remain significant gaps in the literature regarding the development and validation of specific VR prototypes for teaching complex quantum phenomena like the photoelectric effect. Most existing studies have focused on the general advantages of VR in education, such as increased engagement and improved learning outcomes [14, 15, 17, 22], but there is a lack of detailed research on how VR can be specifically tailored to enhance the teaching of the photoelectric effect [19, 23]. Another gap in the literature concerns the validation of VR prototypes in educational settings. While some studies have developed VR simulations for physics education, few have conducted rigorous validation studies to assess their effectiveness in real classroom environments [24, 25]. Validation is essential to determine whether VR simulations can reliably replicate the outcomes of traditional laboratory experiments and whether they can be integrated into the physics curriculum to complement and enhance existing teaching methods.

The purpose of this study is to design and validate a VR prototype specifically for simulating photoelectric effect experiments. This research aims to provide an immersive, interactive learning environment that replicates traditional experimental conditions while also improving students' conceptual understanding and engagement. By focusing on the development and educational validation of this VR tool, the study seeks to contribute to ongoing efforts to innovate physics education by integrating cutting-edge technology. The findings of this research will help fill the current gaps in the literature and offer new insights into the effectiveness of VR as a teaching tool for complex quantum phenomena.

2. Photoelectric experiments

The photoelectric effect has played a pivotal role in shaping our understanding of quantum mechanics and the photon model of light. First explained by Albert Einstein in 1905, the phenomenon involves the emission of electrons from a metal surface when illuminated by light of sufficient frequency [26]. This effect challenged the classical wave theory of light, which could not account for the observed relationship between light frequency and electron emission. Einstein's work not only validated the particle nature of light but also contributed to the development of quantum theory.

The fundamental observation in the photoelectric effect is that when light of a certain frequency strikes a metal surface, it causes the emission of electrons. However, the frequency of the incident light must exceed a threshold value known as the threshold frequency (ν_0). If the light's frequency is below this threshold, no electrons will be emitted, regardless of the intensity of the light. This finding starkly contrasts with classical wave theory, which predicted that the energy transfer to electrons should depend solely on light intensity [27]. The photoelectric effect, therefore, provides strong evidence for the quantisation of light energy, demonstrating that the energy of light is carried in discrete packets or photons. The following equation can express Einstein's formulation of the photoelectric effect:

$$eV_\mathrm{s} = hv - \phi. \tag{1}$$

In this equation, e represents the elementary charge, V_s is the stopping potential required to prevent the most energetic photoelectrons from reaching the anode, h is Planck's constant, ν is the frequency of the incident light, and ϕ is the work function of the metal. The work function, ϕ, represents the minimum energy required to release an electron from the metal surface. When a photon with energy $E = h\nu$ strikes the metal, it transfers its energy to an electron, allowing the electron to overcome the binding energy of the metal. The excess energy manifests as the kinetic energy of the emitted electron, expressed as:

$$KE = eV_\mathrm{s} = hv - \phi. \tag{2}$$

Equation (2) shows that the kinetic energy of the emitted electrons depends solely on the frequency of the incident light rather than its intensity. It highlights the quantum mechanical nature of the interaction between light and matter, as the energy of the photons—and thus the kinetic energy of the electrons—is directly proportional to the light frequency. A typical experimental setup for investigating the photoelectric effect involves directing monochromatic light onto a metal surface within a vacuum tube. As shown in figure 1, a monochromator isolates specific wavelengths from a light source, such as a mercury lamp.

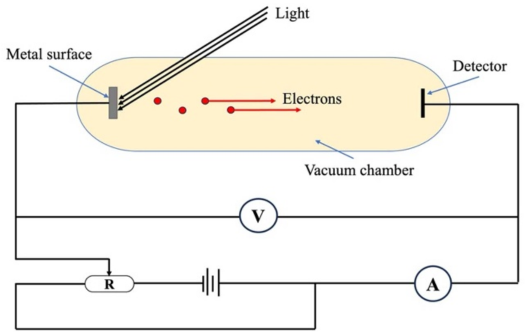

Figure 1. Schematic of the photoelectric effect experiment.

The stopping potential, V_s, is then measured for each wavelength to determine the kinetic energy of the emitted electrons. By plotting the stopping potential against the frequency of the light, key parameters such as the threshold frequency ν_o, the work function ϕ, and Planck's constant h can be determined.

$$v_o = \frac{\emptyset}{h}. \tag{3}$$

This relationship enables the precise calculation of the work function ϕ from experimental measurements of the threshold frequency ν_o, further reinforcing the quantised nature of light and the photon theory proposed by Einstein.

3. Method

3.1. Research design

This study adopted a research and development (R&D) approach to design and validate a VR prototype for conducting photoelectric effect experiments in educational settings. The R&D methodology was selected due to its iterative nature, allowing for continuous prototype refinement through multiple design, development, testing, and validation cycles [28]. This process assures the adequacy of both technical and educational aspects of the end product, which makes it useful and efficient for classroom purposes.

3.2. Design stages

The first stage of the design process involved conducting a comprehensive needs analysis. Data were collected through interviews with physics educators and direct observations of existing laboratory practices. This analysis revealed several key challenges in teaching the photoelectric effect, including limited access to experimental equipment, safety concerns, and students' difficulty grasping abstract quantum phenomena. These findings shaped the design requirements for the VR prototype, ensuring that the tool was tailored to meet the specific needs of physics educators and students.

Following the needs analysis, the development of the VR prototype began with the use of Unity 3D software. Unity 3D was chosen for its flexibility in creating interactive and immersive simulations and its compatibility with various VR hardware. The design of the prototype focused on simulating the key components of the photoelectric effect experiment, including photon-electron interactions, the ability to manipulate variables such as light frequency and intensity, and an intuitive user interface that facilitates user interaction. The development of a VR prototype aimed to create a realistic and engaging virtual environment that closely mirrors traditional laboratory experiments while also providing additional interactive features.

Once the initial prototype was completed, preliminary testing was conducted to evaluate its basic functionality. This phase involved checking the accuracy of the simulation, the responsiveness of the user interface, and the overall usability of the tool. This accuracy refers to the simulation's fidelity to theoretical models and equations, rather than its alignment with experimental data from physical systems. Feedback from initial testing informed further refinements to the prototype. This stage was critical for ensuring the VR tool met the basic requirements before proceeding to more rigorous validation processes.

3.3. Validation stage

The validation process was a critical component of the study, as it assessed both the educational and technical effectiveness of the VR prototype [28]. A panel of three experts, including two quantum physics specialists and one educational practitioner, was assembled to evaluate the prototype. The experts assessed various aspects of the VR tool, including the accuracy of the photoelectric effect simulation, the educational value of the content, the usability of the user interface, and the overall suitability of the tool for classroom teaching.

Data for the validation were collected through questionnaires and open-ended feedback forms, which allowed the experts to provide detailed evaluations of each criterion. The iterative design process continued during this stage, as the feedback from the experts was used to refine the prototype further. This process ensured that the VR tool's final version was accurate in its scientific representation and effective as an educational resource. The expert panel provided positive feedback on the accuracy and educational value of the VR simulation with some suggestions on user engagement and reducing motion sickness effects during extensive use.

4. Results

4.1. Design of the VR prototype

This study developed a VR prototype designed to simulate the core components of the photoelectric effect experiment. The primary aim was to provide students with an immersive, interactive experience that mirrors real-world laboratory setups. The VR simulation allows users to interact with and visualize the simulated emission of electrons under various conditions by adjusting the frequency and intensity of light. Users can record the corresponding results and analyse the relationships between variables such as photon energy, work function, and electron emission. It is important to note that these visualizations represent theoretical behaviours modelled within the simulation, rather than empirical observations of physical phenomena. The main interface of the VR simulation replicates a typical experimental setup, as shown in figure 2, allowing users to adjust variables and visualise results in real time.

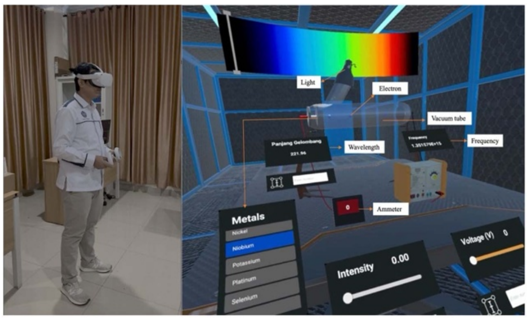

Figure 2. The main view of the VR prototype for the photoelectric effect experiment.

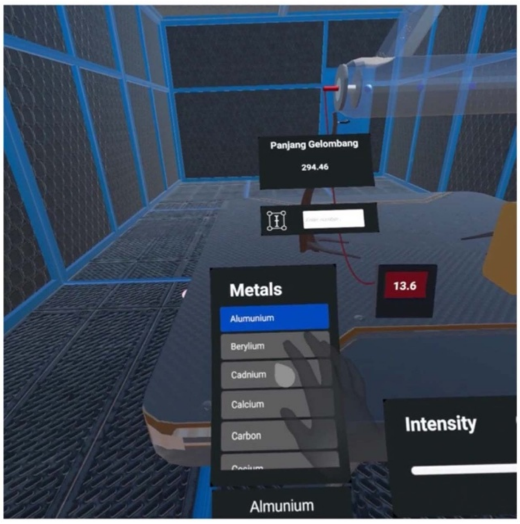

Figure 3. Selectable metal display in photoelectric effect experiment with VR.

4.2. The effect of metal types on threshold frequency

One of the most notable features of the VR prototype is its ability to simulate the behaviour of 25 different metals, each with a specific threshold frequency. The threshold frequency is the minimum light frequency required to eject electrons from a metal surface. If the frequency of the light is below this threshold, no electrons are emitted, regardless of the intensity. This feature allows students to investigate how different materials respond to varying light frequencies and wavelengths. This reinforces a fundamental principle of quantum physics: electron emission is frequency-dependent, not intensity-dependent. Figure 3 shows examples of metals that can be selected in the developed VR prototype.

Table 1 presents simulation results for five metals, illustrating the variation in work functions, threshold frequencies, and wavelengths among them. The results highlight how each

Table 1. Simulation results of the photoelectric effect experiment with VR for selected metals.

Type of metal	Threshold wavelength (nm)	Threshold frequency (Hz)	Work function (eV)
Sodium (Na)	540	5.55×10^{14}	2.29
Calcium (Ca)	428	7.01×10^{14}	2.90
Zinc (Zn)	291	1.03×10^{15}	4.26
Copper (Cu)	265	1.13×10^{15}	4.67
Platinum (Pt)	196	1.53×10^{15}	6.33

metal's work function determines its distinct response to incident light. Sodium (Na), for example, has a low work function of 2.28 eV, corresponding to a threshold frequency of 5.55×10^{14} Hz and a threshold wavelength of 540 nm. In contrast, platinum (Pt) has a much higher work function of 6.35 eV, requiring a threshold frequency of 1.53×10^{15} Hz and a threshold wavelength of 196 nm for electron emission. These results demonstrate the VR tool's accuracy in representing the theoretical behaviour of different metals and provide an interactive platform for students to explore the relationship between photon energy, work function, and electron emission.

4.3. Dependence of electron kinetic energy on light frequency

The VR simulation also allows students to investigate the relationship between the kinetic energy of emitted electrons and the frequency of incident light. In this experiment, the frequency of the light is increased while keeping the intensity constant. The simulation results clearly showed that once the light frequency exceeds the metal's threshold, the kinetic energy of the emitted electrons increases proportionally with the frequency. This relationship between frequency and kinetic energy is consistent with Einstein's equation for the photoelectric effect, which predicts that the kinetic energy of emitted electrons is directly proportional to the frequency of the incident photons.

The stopping potential plays a crucial role in understanding this relationship. The stopping potential is the voltage required to bring the kinetic energy of the emitted electrons to zero. The magnitude of this stopping potential is directly related to the kinetic energy of the electrons.

(a) (b)

Figure 4. Comparison before and after the application of stopping potential in a photoelectric effect experiment.

As the frequency of the incident light increases, the kinetic energy of the emitted electrons also increases, requiring a higher stopping potential to halt them. Therefore, the stopping potential is a measure of the maximum kinetic energy of the emitted electrons. Figure 4 provides a detailed representation of the stopping potential experiment through two comparative snapshots, highlighting the conditions before and after applying the stopping potential. This visual elucidates the relationship between the incident light frequency and the kinetic energy of emitted electrons in the photoelectric effect.

As we can see in figure 4(a), the experimental setup is depicted before the application of any stopping potential. The voltage is set at 0 V, allowing the emitted electrons to travel unimpeded to the detector. The intensity of the light source is maintained at 0.66, while the frequency of the incident light is recorded at 1.19×10^{15} Hz, corresponding to a wavelength of 250.89 nm. Under these conditions, the current flow is observed at 10.5 μA, indicating that electrons are emitted and detected due to the incident light's energy surpassing the material's work function. However,

Table 2. Variations in light frequency and kinetic energy for caesium.

Threshold wavelength (nm)	Threshold frequency ($\times 10^{14}$ Hz)	Stopping potential (V)	Maximum kinetic energy (eV)
650	4.61	0.00	0.00
600	5.00	0.13	0.13
550	5.45	0.31	0.31
500	6.00	0.54	0.54
450	6.67	0.82	0.82

in figure 4(b), after applying a stopping potential of 0.847 V, the electron emission process undergoes a significant change. The current reading drops to 0 μA, signifying that the applied voltage is sufficient to halt the kinetic energy of the emitted electrons. The intensity and frequency of the light source remain constant, as does the wavelength. However, the cessation of the current indicates that the stopping potential has fully countered the energy of the emitted electrons, thereby preventing them from reaching the detector. Thus, figure 4 provides a clear example of how stopping potential directly influences the detection of emitted electrons. The comparison between the two states—before and after applying the stopping potential—demonstrates the fundamental principles underlying the photoelectric effect and the calculation of the maximum kinetic energy of the emitted electrons.

As shown in table 2, which presents the variations in light frequency and the corresponding kinetic energy of emitted electrons for caesium, the behaviour of the photoelectric effect is evident. At the lowest frequency tested, 4.61×10^{14} Hz, no electrons were emitted, as the energy provided by the photons was insufficient to overcome the work function of caesium. This is consistent with the concept of a threshold frequency—below this frequency, the energy of the incident photons is too low to eject electrons from the metal surface. However, electrons began to be emitted once the frequency exceeded 5.00×10^{14} Hz, which is above the threshold frequency for caesium, as indicated by the non-zero stopping potential. Table 2 shows that as the frequency increases, the stopping potential and the maximum kinetic energy of the electrons also increase. For example, at a frequency of 6.67×10^{14} Hz, the stopping potential reaches 0.82 V, corresponding to a kinetic energy of 0.82 eV for the emitted electrons. This demonstrates the direct relationship between the incident light frequency and the emitted electrons' kinetic energy, per the photoelectric effect theory.

4.4. Effect of light intensity on electron emission

The VR prototype also allows students to explore how varying light intensity affects the number of emitted electrons. In this set of experiments, the light frequency was kept constant above the threshold while the intensity was varied. The results show that as the intensity of the light increases, the number of emitted electrons increases proportionally, as reflected by a rise in photocurrent. However, the kinetic energy of the electrons remained constant across all intensity levels. This finding demonstrates theoretical consistency with the quantum mechanical principle, that the kinetic energy of the emitted electrons is determined by light frequency, not intensity. Table 3 presents caesium data, demonstrating how photocurrent increases with light intensity while the stopping potential remains constant.

As shown in table 3, the photocurrent increases as the light intensity is raised from 20% to 100%, reflecting a greater number of emitted electrons. However, the stopping potential remains unchanged at 1.16 V across all intensity levels, which confirms that the energy of the electrons depends only on the frequency of the light and not on its intensity. These experimental results support the quantum theory of light, particularly the idea that the kinetic energy of emitted electrons is proportional to the frequency of the incident photons, while the number of electrons emitted is directly related to light intensity.

Table 3. Variations in light intensity at constant frequency for caesium.

Light intensity (%)	Photocurrent (μA)	Stopping potential (V)	Kinetic energy (eV)
20	0.4	1.16	1.16
40	0.8	1.16	1.16
60	1.2	1.16	1.16
80	1.6	1.16	1.16
100	2.0	1.16	1.16

Thus, this VR simulation provides an effective and interactive way to demonstrate the principles of the photoelectric effect experiment.

4.5. Validation results

The validation results of the VR prototype for photoelectric effect experiments were comprehensively assessed after incorporating revisions based on initial feedback from validators. The process involved ten participants, comprising five experts (physics specialists and educational technology researchers) and five practitioners (experienced physics teachers). The validators evaluated the tool across multiple dimensions, including technical accuracy, usability, educational value, and its suitability for classroom implementation. Table 4 shows the key comments from validators and the corresponding revisions implemented.

Then after the initial validation by experts and practitioners, the author made revisions and returned to further validation. The second result as the final validation can be seen in table 5.

As we can see in table 5, the VR prototype demonstrated exceptional performance in key areas, with accuracy (Mean = 4.80, SD = 0.42) and visual quality (Mean = 4.80, SD = 0.42) receiving the highest ratings. Validators consistently highlighted that the simulation closely aligns with theoretical principles, particularly Einstein's photoelectric equation, while presenting the phenomena in an engaging and visually effective manner. One expert remarked, *'The simulation accurately represents photon-electron interactions and provides a clear visualization of quantum principles, making it highly valuable for educational purposes.'*

Usability and engagement also scored highly, with validators commending the inclusion of step-by-step tutorials and interactive features such as quizzes and checkpoints. These additions addressed prior feedback regarding the tool's initial learning curve and enhanced its effectiveness in fostering active student participation. As one practitioner noted, *'The interactive quizzes are an excellent addition, allowing students to consolidate their understanding while engaging with the simulation.'*

Despite these strengths, some challenges remain. The extent to which the VR tool ensures physical comfort, particularly in mitigating motion sickness, received a lower mean score of 3.90 (SD = 0.57). Validators observed that while smoother transitions and refined motion dynamics reduced discomfort, some users still experienced minor dizziness during extended use. Furthermore, the cost analysis for implementation and maintenance (Mean = 4.20, SD = 0.42) highlighted concerns about financial feasibility for institutions with limited budgets. These areas warrant further exploration in future iterations of the VR tool.

5. Discussion

One of the major challenges in teaching physics, particularly quantum mechanics, is the difficulty of conducting real-life experiments due to limited access to laboratory equipment, safety concerns, and the high cost of maintaining sophisticated experimental setups [9, 17]. This study demonstrates that VR can address these challenges by providing a virtual laboratory environment where students can engage with concepts that are otherwise inaccessible. The ability to simulate different metals and manipulate variables such as light intensity and frequency offers students a broader and more comprehensive

Table 4. Validator comments and revisions implemented for VR prototype validation.

No	Key comment from validators	Revisions implemented
1	*The simulation is accurate in depicting the photoelectric effect. However, the lack of detailed initial instructions may discourage new users*	A step-by-step procedure manual was created to guide users through the VR tool, ensuring that both novice and experienced users can effectively navigate the simulation. The tutorial includes visual and textual instructions covering key functionalities, such as adjusting light frequency and intensity, observing electron emissions, and analysing results
2	*The visual design is appealing, but motion sickness may occur during prolonged use*	Visual transitions were optimized to reduce rapid movements, and smoother motion dynamics were implemented to minimize motion-related discomfort. Additional adjustments included calibrating animations to be less abrupt while maintaining engagement
3	*The simulation should include photocurrent behaviour when the applied stopping potential is high*	A new feature was added to simulate photocurrent behaviour, including scenarios where the stopping potential prevents electrons from reaching the detector. This update enhances the realism of the simulation, reinforcing theoretical concepts such as the relationship between stopping potential and photocurrent.
4	*The tool is easy to navigate, but compatibility with a wider range of devices should be considered*	Compatibility testing was expanded to include various VR hardware and PC configurations, ensuring the tool can operate on a broader range of devices. This improvement addresses accessibility concerns and allows for wider adoption across educational institutions
5	*Add the ability to test multiple metals with different threshold frequencies*	The prototype now includes a selection of metals with varying threshold frequencies, allowing students to explore how different materials respond to changes in light frequency and intensity.

learning experience. However, VR is not intended to replace traditional laboratory experiments but rather to complement them by offering a safe, scalable, and cost-effective alternative for specific scenarios. This approach is particularly valuable for institutions in developing countries where expensive equipment may not be available. Additionally, senior high schools, which often include the photoelectric effect in their physics curriculum, can benefit from this tool to help students visualize and understand the theory despite lacking laboratory resources for hands-on experimentation.

The results align with prior research, which has highlighted the benefits of using VR to simulate complex experiments in educational contexts [13, 16, 17]. For instance, VR allows students to perform multiple iterations of an experiment without the risk of damaging equipment or incurring additional costs. Additionally, the immersive nature of VR enables students to experiment with potentially hazardous scenarios—such as manipulating high-frequency light—without any physical risk. This enhances safety and allows educators to introduce a wider range of experimental conditions that would be difficult to replicate in a traditional laboratory setting.

As demonstrated by this study, one of the primary advantages of using VR in education is its ability to provide an immersive learning environment that allows students to explore complex scientific concepts through active experimentation. The VR prototype developed for the photoelectric effect offers students the opportunity to manipulate variables such as light frequency and intensity in a highly interactive manner. Through this simulation, users can directly observe and explore how changes in these variables affect electron emission, thereby investigating their alignment with quantum mechanical principles. This hands-on

Table 5. The validation results of the VR prototype for photoelectric effect experiments.

No	Statements	Validation score mean	Standard deviation
1	The accuracy of the VR simulation in representing the photoelectric effect	4.80	0.42
2	Ease of use and navigation within the VR environment	4.40	0.52
3	The effectiveness of VR in helping students understand the concept of the photoelectric effect	4.60	0.52
4	Suitability of VR for classroom teaching	4.40	0.52
5	The degree to which VR allows active user interaction	4.40	0.52
6	The ability of VR to engage students in learning	4.60	0.52
7	Alignment of VR content with the physics curriculum	4.70	0.48
8	Visual quality and the effectiveness of VR in depicting concepts visually	4.80	0.42
9	Ease of installation and configuration of VR	4.40	0.52
10	Compatibility of the VR prototype with various devices (computer, VR headset, etc)	4.50	0.53
11	The extent to which VR ensures the physical safety and health of users, including motion sickness prevention features	3.90	0.57
12	The ability of VR to support various learning methods	4.30	0.48
13	The flexibility of VR to adapt to different learning needs	4.30	0.48
14	Effectiveness of VR in utilising learning time, including the time required to complete experiments	4.50	0.53
15	Cost analysis for implementing and maintaining VR in an educational setting	4.20	0.42

approach not only bridges the gap between theoretical concepts and practical understanding but also addresses limitations often found in traditional teaching methods. Furthermore, this interactive approach aligns with previous studies, which have shown that VR technology improves students' comprehension of abstract scientific concepts by offering a more experiential form of learning [14, 15, 18].

Moreover, the simulation results, particularly those related to the kinetic energy of electrons as a function of light frequency, directly reinforce key theoretical concepts in quantum mechanics. The findings confirm Einstein's equation for the photoelectric effect, demonstrating the proportional relationship between light frequency and the kinetic energy of emitted electrons. These results provide tangible evidence of the quantum nature of light, a concept that can be difficult for students to grasp through theoretical instruction alone. Similar studies have noted that VR simulations help bridge the gap between theory and practice, enabling students to visualise and experiment with phenomena that are otherwise challenging to teach using conventional methods [17, 20].

The results of the study showed that the immersive and interactive nature of VR has been shown to capture students' attention more effectively than traditional instructional techniques, leading to higher levels of motivation and curiosity [17]. In the context of teaching the photoelectric effect, which involves complex and abstract quantum concepts, keeping students engaged is critical for successful learning outcomes. The validation results suggest that students are more likely to actively participate in learning when using the VR tool, as they can interact with the experiment and explore its outcomes in real-time. This increased engagement has broader implications for improving learning outcomes in physics education. Studies have consistently shown that higher engagement levels correlate with enhanced retention of information and a deeper understanding of complex topics [29, 30]. By fostering a more active and participatory learning environment, the VR prototype developed in this study could help educators overcome some of the persistent challenges in teaching advanced physics topics, such as the photoelectric effect and quantum mechanics in general.

The validation process conducted by the expert panel confirmed that the VR prototype is both technically accurate and educationally valuable. The high accuracy, ease of use, and visual quality scores indicate that the simulation reliably represents the photoelectric effect. This is crucial for ensuring the tool can be integrated into physics curricula to complement or replace traditional laboratory experiments. However, concerns regarding motion sickness and prolonged use of the VR headset highlight the need for further refinement, particularly in addressing user comfort.

Although some limitations were identified, such as the potential for motion sickness during extended use, these issues are not insurmountable. Implementing proper usage guidelines, such as limiting session duration and ensuring ergonomic headset design, could mitigate these concerns. Moreover, cost analysis revealed that while VR systems may involve an initial investment, their long-term benefits—such as reducing the need for expensive physical equipment and providing a safer learning environment—could outweigh the costs, making VR a sustainable educational tool in the long run.

6. Conclusion

This study presents the development and validation of a VR prototype designed to simulate the photoelectric effect experiment. The results demonstrate that the VR prototype accurately replicates the conditions of real-world laboratory experiments while offering additional flexibility and safety. By simulating the behaviour of different metals and enabling the exploration of key quantum mechanics principles, the VR tool provides a valuable educational resource that is both engaging and effective. Its potential for enhancing student motivation and participation was further confirmed through expert validation, with high ratings for accuracy, educational value, and user engagement.

The novelty of this work lies in its ability to provide students with an immersive, interactive platform where they can manipulate critical variables such as light frequency and intensity, observe electron emissions, and engage directly with complex quantum phenomena. The significance of this work extends beyond the immediate benefits of improved understanding of the photoelectric effect. The VR prototype addresses broader issues in physics education, such as limited access to laboratory equipment, safety concerns, and the challenges of teaching abstract scientific concepts. This technology offers a long-term solution to these persistent barriers in physics instruction by providing a scalable and adaptable virtual environment.

Looking forward, future work will focus on expanding the scope of the VR tool to cover additional experiments and quantum phenomena, as well as improving user interaction and comfort to reduce potential motion sickness. There is also scope for integrating the VR prototype into broader educational frameworks, allowing it to complement traditional laboratory practices and enhance the overall learning experience in physics education. Further research could explore the long-term impacts of VR-based learning on student outcomes and its adaptability to different learning styles and curricula.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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