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Developing a Virtual Reality Simulation of the Michelson-Morley Experiment for Physics Education: Design, Validation, and Educational Impact

Muh. Alka
Universitas Muhammadiyah Makassar
Makassar, Indonesia

Irwan Akib
Universitas Muhammadiyah Makassar
Makassar, Indonesia

Hartono Bancong*
Universitas Muhammadiyah Makassar
Makassar, Indonesia

Abstract. The Michelson-Morley experiment is a foundational experiment in modern physics that played a critical role in shaping our understanding of space-time and the speed of light. However, reproducing this historically significant experiment in an educational setting poses substantial logistical challenges due to the complexity and precision of the required equipment. This study presents the development and validation of a virtual reality prototype designed to simulate the Michelson-Morley interferometer experiment. Using a research and development methodology, the virtual reality prototype replicated the experimental setup, allowing students to adjust parameters, such as mirror angles and laser types, to observe real-time interference patterns. Validation by three experts, including two experimental physicists and one educational practitioner, yielded an average score of 4.27 out of 5. The prototype excelled in simulation accuracy, educational effectiveness, and curriculum alignment, with perfect scores (5.00) for these indicators. The findings highlight the virtual reality tool's effectiveness in enhancing students' understanding of wave interference and light behavior. Despite minor concerns about motion sickness and implementation costs, the virtual reality approach demonstrates considerable promise for enriching physics education.

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* Corresponding author: *Hartono Bancong, hartono.b.b@unismuh.ac.id*

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1. Introduction

The Michelson-Morley experiment, first performed in 1887, remains one of the most influential experiments in physics. This experiment fundamentally challenged the existence of the "luminiferous ether"—a medium once hypothesized to carry light waves (Manley, 2023; Roy, 2017). The experiment, designed by Albert A. Michelson and Edward W. Morley, aimed to detect Earth's motion through the hypothesized ether by assessing variations in light speed along two perpendicular interferometer paths. The expected outcome was that light would travel at different speeds depending on its orientation relative to Earth's motion through the ether (Smid, 2017; Szostek & Szostek, 2018). However, the experiment's null result contradicted the ether theory, leading to significant advancements in the understanding of space-time and motion, particularly through Albert Einstein's theory of special relativity (Gao, 2016; Manley, 2023; Roy, 2017).

With advancements in technology, the Michelson-Morley experiment was revisited and refined using modern tools, such as air-water diopter as a beam splitter and GPS technology (Manley, 2023; Silva et al., 2023). These enhancements have continued to validate the original null result, reinforcing the concept that the speed of light remains constant across all inertial frames (Nagel et al., 2015; Klinaku, 2022; Croca, 2001). Despite ongoing searches for deviations from Lorentz invariance, the Michelson-Morley experiment stands as a pillar of modern physics, emphasizing the importance of experimental precision in discrediting long-held scientific theories (Bhadra et al., 2023; Szostek & Szostek, 2018.

Physics education today faces challenges such as limited accessibility to advanced equipment, the need for engaging instructional methods, and the integration of modern technologies to bridge the gap between theory and practice (Bancong & Song, 2020). These issues are particularly evident in historically significant but complex experiments, such as the Michelson-Morley interferometer, which requires precise alignment and sophisticated equipment. Due to these logistical constraints, many educational institutions struggle to provide practical and firsthand experiences with this experiment (Klinaku, 2022; Pathare & Kurmude, 2016). Consequently, students may find it difficult to fully comprehend the null result and its implications for modern physics (Franklin, 2016). To address these limitations, virtual reality (VR) has emerged as a promising solution. VR offers fully immersive and interactive environments that facilitate hands-on learning without the need for physical equipment. Compared to other methods, such as computer-based simulations or augmented reality, VR provides greater immersion and engagement. It allows students to manipulate experimental parameters in real-time and visualize complex phenomena in a three dimensional (3D) space.

VR technology offers an immersive platform where students can engage in scientific experiments in a simulated environment, enabling hands-on interaction without requiring physical equipment (Angelis, 2022; Canright, 2024). This approach not only made scientific education more accessible but also enhanced student engagement and conceptual understanding (Husnaini & Chen, 2019; Porter et al., 2020). VR-based learning tools demonstrate significant potential in helping students grasp complex concepts, particularly in fields such as optics and wave interference (Croca et al., 2019; Price & Price-Mohr; 2019 Zakharov et al., 2020). Therefore, by simulating the Michelson-Morley experiment within a VR environment, students can manipulate an interferometer, adjust experimental parameters, and observe the resulting interference patterns in real time, fostering a deeper understanding of the experiment's significance and historical context.

This study aimed to design and validate a VR prototype that replicates the Michelson-Morley interferometer experiment in a laboratory setting. By doing so, it sought to enhance students' understanding of light wave interference and the historical importance of the Michelson-Morley experiment. This VR tool not only simulated the experimental conditions of the original format but also provided an interactive and engaging platform that bridges the gap between theoretical learning and practical experimentation. The research questions of the study are as follows:

1. Can the developed VR simulation accurately replicate the Michelson-Morley experiment in an educational context?
2. What are the validation results of the Michelson-Morley experimental design using VR?

2. Michelson-Morley Experiment

The Michelson-Morley experiment, initially conducted by Albert A. Michelson and Edward W. Morley in 1887, remains a cornerstone in modern physics. The experiment aimed to detect the "luminiferous ether," a theoretical medium thought to permeate space and allow the propagation of light waves (Manley, 2023; Roy, 2017). Ether's theory was widely accepted at the time and the experiment was designed to measure differences in the speed of light as the Earth moved through this medium (Abreu & Guerra, 2007). The expectation was that light would travel at different speeds depending on whether it was aligned with or perpendicular to Earth's motion through the ether (Smid, 2017; Rapport, 2022; Roy, 2017).

The theoretical foundation for the Michelson-Morley experiment assumed that, like sound, light required a medium for travel (Abreu & Guerra, 2007; Croca et al., 2019). This hypothetical medium, known as the ether, was believed to be stationary, and Earth's motion through this medium was expected to result in observable variations in light speed. The expectation was that light traveling parallel to Earth's motion through the ether would move slower compared to light moving perpendicularly (Roy, 2017; Rapport, 2022). The experiment, through its ingenious interferometer design, sought to measure the expected difference in light speed along two perpendicular paths of the apparatus (Smid, 2017).

The experimental setup, as illustrated in Figure 1, consisted of an interferometer that split a light beam into two perpendicular paths. If the ether existed, the light traveling in the direction of Earth's motion should have taken longer to return than the perpendicular beam. This would result in a measurable fringe shift in the interference pattern, thus indicating the presence of the ether (Manley, 2023). However, the results were unexpected: no detectable difference in the speed of light was observed in either direction, leading to a "null result." This contradicted the ether theory and suggested that the ether was either non-existent or undetectable by this experiment (Rahaman, 2022; Szostek & Szostek, 2018).

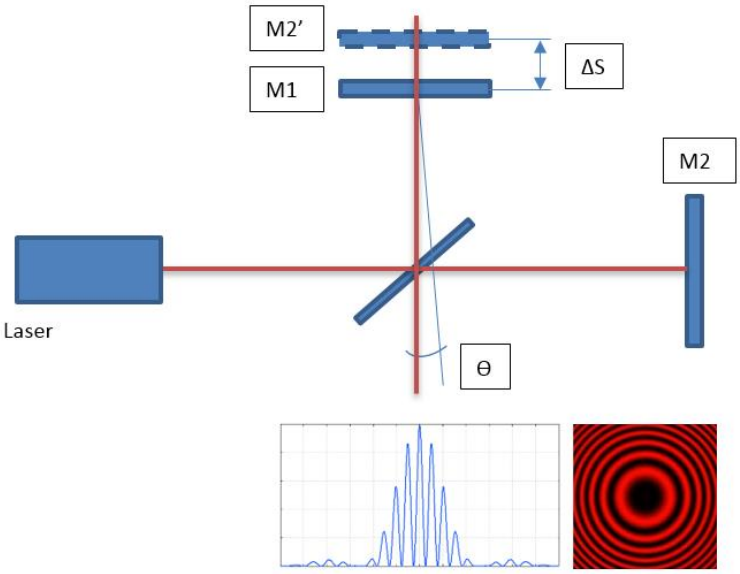


Figure 1: The illustration of the Michelson-Morley experiment (PhysicsOpenLab, 2020)

The null result of the Michelson-Morley experiment was not anticipated. The lack of any observable fringe shift implied that light's speed remained constant in all directions, independent of Earth's motion through space. This outcome directly contradicted the predictions of ether theory and forced a re-evaluation of fundamental assumptions regarding light and motion (Nagel et al., 2015). The Michelson-Morley experiment's null result had profound implications for the field of physics. It raised critical questions about the nature of light and the structure of space-time, eventually contributing to the downfall of the ether hypothesis.

Hendrik Lorentz and others attempted to retain the ether concept by introducing Lorentz transformations, mathematical equations that suggested time and space were relative to motion, effectively explaining why the speed of light appeared constant in all reference frames (Szostek & Szostek, 2018). However, it was Albert Einstein who offered a definitive resolution to the implications of the Michelson-Morley experiment through his special theory of relativity, published in 1905. Einstein discarded the ether concept entirely, asserting that the laws of physics are uniform across all inertial frames and that the speed of light in a vacuum remains constant, regardless of the observer's or the source's motion. This groundbreaking theory fundamentally altered the understanding of space and time, marking a shift from the classical mechanics of Newton to the relativistic framework that defines modern physics (Abreu & Guerra, 2007; Szostek & Szostek, 2018)

3. Methods

3.1 Research Design

This study used a research and development methodology (Creswell & Creswell, 2018) to design and validate a VR prototype for conducting the Michelson-Morley interferometer experiment in a laboratory setting. The research and development process ensured the continuous refinement of the VR prototype through multiple cycles of design, testing, and validation. This methodology was chosen to address the educational needs associated with the Michelson-Morley interferometer experiment while ensuring the VR tool functioned seamlessly in an academic setting.

3.2 Design Stages

The development process started with a comprehensive needs analysis (Creswell & Creswell, 2018). Physics educators were interviewed, and laboratory practices were observed to identify the primary challenges students and instructors faced in conducting traditional Michelson-Morley experiments. Common issues included complex alignment of interferometer components, difficulty in interpreting the null result, and limited access to precise and costly laboratory equipment. These insights guided the design of the VR prototype, ensuring that it addressed these educational challenges by offering an accessible and engaging virtual platform.

The VR prototype was developed using Unity 3D software, supported by high-performance hardware: a gaming laptop equipped with an Intel i7 processor, 16 GB RAM, and an NVIDIA RTX 3060 graphics card, and compatible with popular VR headsets, such as Oculus Rift and HTC Vive. The software and hardware choices ensured seamless operation and high-quality simulation performance. Key features of the prototype included realistic representations of the Michelson interferometer components, such as the beam splitter and mirrors, as well as an intuitive interface that allowed users to adjust variables, such as the mirror angles and beam splitter position. These interactive elements were crucial in helping students gain a deeper understanding of the principles underlying light wave interference.

Once the initial design was completed, an initial version of the VR prototype was developed. This version was subjected to preliminary testing to verify fundamental functionalities, including accurate light interference simulation and responsive user interface performance. Early testing focused on identifying and resolving any technical issues that could impair usability or educational value. This stage ensured that the VR tool met basic educational and technical requirements prior to formal validation.

3.3 Validation Stages

To validate the VR prototype, a panel of three experts was formed, comprising two experimental physicists and one educational practitioner. These experts assessed the prototype based on multiple criteria, including the accuracy of the interferometer simulation, user interface design, educational content alignment, and overall usability in classroom settings. Data were collected using detailed

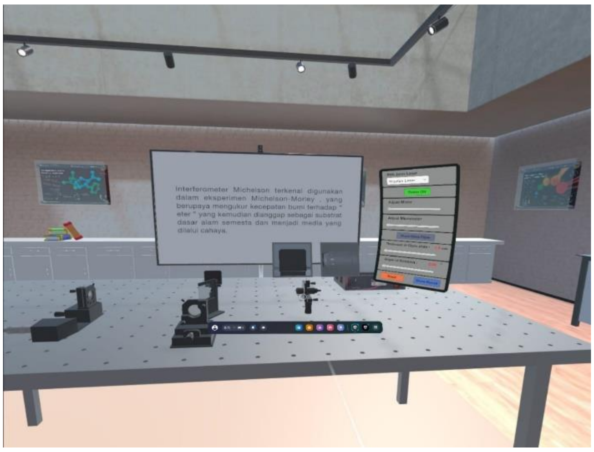
Likert-scale questionnaires and qualitative feedback forms, ensuring reliable and in-depth input on each aspect of the VR tool. The validation process was iterative, with expert feedback guiding successive refinements to address identified issues and enhance functionality. The high Cronbach's alpha value of 0.85 confirmed the reliability of the assessment tools, reinforcing the robustness of the validation process. The final version of the VR prototype was tested in a classroom setting to ensure that it effectively simulated the Michelson-Morley experiment.

Although the prototype underwent initial classroom trials to test feasibility, this study has primarily focused on its design and validation. Feedback from classroom trials, including insights into usability and engagement, was incorporated to optimize the VR tool for future educational implementation. A detailed analysis of the learning outcomes from classroom trials will be presented in a separate study, allowing for a thorough exploration of the tool's impact on student comprehension and engagement.

4. Results

4.1 Design of Experiments

This research examined the replication of the Michelson-Morley experiment using modern VR technology to simulate light wave interference patterns. By employing VR, the experiment enabled a more interactive and precise examination of light behavior, where users could manipulate experimental variables such as laser source, lens types, and the thickness of glass plates. Figure 2 shows the main interface of the Michelson interferometer design in the VR environment, illustrating key components and the user interface.



Interferometer Michelson terkenal digunakan dalam eksperimen Michelson-Morley , yang berupaya mengukur kecepatan bumi terhadap " eter " yang kemudian dianggap sebagai substrat dasar alam semesta dan menjadi media yang dilalui cahaya.

Figure 2: The main VR interface for the Michelson-Morley interferometer design

The VR setup effectively simulated the Michelson interferometer mechanism, splitting a monochromatic laser beam into two paths. The beams were reflected and recombined, creating interference patterns on a virtual screen. These patterns resulted from differences in the paths traveled by the two beams. The flexibility of the VR platform permitted adjustments to key variables, such as the beam splitter's angle and the glass plate's thickness. These variations demonstrated the high sensitivity of the interferometer to light path changes, underscoring its effectiveness in measuring light wave properties. Figure 3 presents the interference patterns generated by the experiment in VR, providing a clear visual representation of the patterns formed as the two beams recombined.

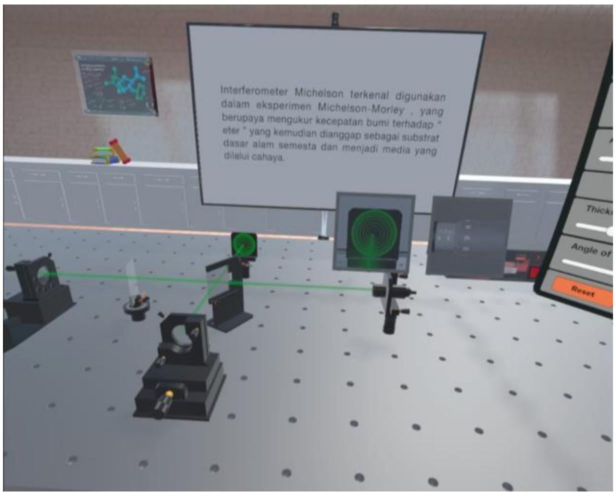


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Figure 3: Interference pattern formed in the VR environment.

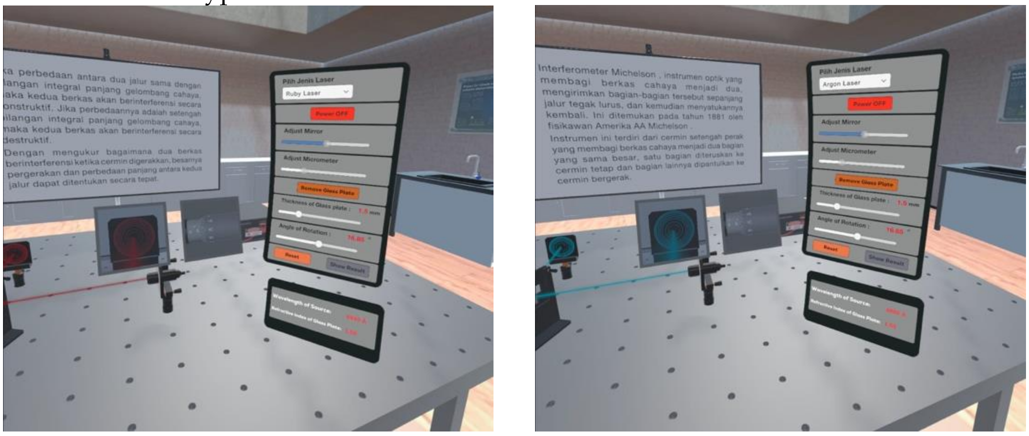
In this virtual setup, four different types of lasers—krypton, helium-neon (he-ne), argon, and ruby—were used to generate interference patterns, with each laser producing distinct patterns corresponding to its wavelength. These patterns, arising from differences in path lengths, were visually displayed on a virtual screen for users to observe. The VR platform enabled precise adjustments to experimental parameters, ensuring high control over the experimental setup. This functionality replicated the Michelson interferometer's sensitivity under real-world conditions, reinforcing the principles of wave interference and light propagation. Table 1 presents the wavelengths measured for the different laser types used in the experiment, illustrating variations in interference patterns caused by differing wavelengths.

Table 1: Wavelengths and interference patterns of different laser sources

Laser type	Wavelength (nm)	Interference pattern characteristics
Krypton	647	Stable fringes, moderate spacing between fringes
Helium-neon	632.8	Highly stable, closely spaced interference fringes
Argon	488	Distinct fringes, wider spacing than Krypton
Ruby	694.3	Clear, widely spaced fringes, best for visual demonstrations

The ability to adjust parameters, such as mirror angles, beam splitter orientation, and the thickness of glass plates, illustrated the interferometer's sensitivity to light path variations. For instance, adjusting the glass plate thickness altered the optical path length, consequently affecting the interference fringes. The VR interface offered a real-time, intuitive platform to manipulate these variables, delivering an immersive and educational experience beyond what traditional setups could readily replicate. The helium-neon laser, in particular, was found to produce the most stable and consistent interference fringes, making it ideal for educational and research purposes. Figure 4 shows the interference patterns generated from different laser wavelengths.

a Krypton Laser b He-Ne Laser



c Argon Laser d Ruby Laser

Figure 4: **The interference patterns formed by the four different lasers (krypton, he-ne, argon, and ruby)**

4.2 Validation Results

The validation of the VR prototype represented a crucial phase in evaluating its educational effectiveness and technical accuracy. The validation process involved a panel of three experts—two in experimental physics and one educational practitioner—who evaluated the tool based on several criteria, such as the accuracy of the simulation, ease of use, educational value, and overall usability. Their feedback was gathered through detailed questionnaires, with the results shown in Table 2.

Table 2: Validation results for the Michelson-Morley Experimental design in VR

No	Statements	Validator score			Mean	Standard deviation
		Expert 1	Expert 2	Practitioner		
1	The accuracy of the VR simulation in representing the Michelson-Morley experiment.	5	5	5	5.00	0.00
2	Ease of use and navigation within the VR environment	5	4	4	4.33	0.58
3	The effectiveness of VR in helping students understand the concept of light interference and the Michelson-Morley experiment.	5	5	5	5.00	0.00
4	The degree to which VR allows active user interaction	4	4	4	4.00	0.00
5	Alignment of VR content with the physics curriculum and learning objectives.	5	5	5	5.00	0.00
6	Visual quality and effectiveness of VR in depicting concepts visually (interference patterns, light splitting, etc.).	5	4	5	4.67	0.58
7	Ease of installation and configuration of the VR system.	4	4	4	4.00	0.00
8	The extent to which VR ensures the physical safety and health of users, including motion sickness prevention	4	3	3	3.33	0.58
9	Effectiveness of VR in utilizing learning time, including the time required to complete experiments	4	4	4	4.00	0.00
10	Cost analysis for implementing and maintaining VR in an educational setting	4	3	3	3.33	0.58

One of the most notable findings was the high level of accuracy in the VR simulation. The simulation received a perfect mean score of 5.00, with a standard deviation of 0.00, reflecting unanimous agreement among the validators. This indicates that the VR tool accurately replicated the theoretical principles of the Michelson-Morley experiment, especially in illustrating light interference and wave behavior. Similarly, the VR simulation's effectiveness in aiding student comprehension of these complex concepts also received a perfect score of 5.00. This indicates the substantial educational value of the tool in making abstract physical phenomena comprehensible.

The ease of use and navigation within the VR environment received positive feedback, with a mean score of 4.33 and a standard deviation of 0.58. Although the VR tool was considered user-friendly, minor improvements in the interface could further enhance its usability. In terms of user interaction, the VR platform offered an engaging experience, enabling students to manipulate experimental variables and observe real-time results. This aspect received a mean score of 4.00, suggesting that the tool successfully facilitates active learning, though there may be room for further development in enhancing user engagement.

The alignment of the VR content with the physics curriculum and learning objectives was also a strong point, with a perfect score of 5.00. This suggests that the VR tool is suitable for educational use, fulfilling physics education standards and requirements. The visual quality of the simulation, particularly in depicting light interference patterns and other key concepts, received high ratings, with a mean score of 4.67. The validators commended the visuals for their clarity and precision, contributing to an immersive and effective learning experience.

However, some areas were identified as needing improvement. Physical safety and health considerations, particularly in preventing motion sickness, received a lower score of 3.33, indicating that while the VR tool is generally safe, some users might feel discomfort during prolonged use. This issue, although not severe, merits attention to ensure comfort and accessibility for all users. Additionally, the cost of implementing and maintaining the VR system was noted as a potential concern, with a mean score of 3.33. This suggests that while the VR tool offers significant educational benefits, its financial viability could be challenging for some institutions.

5. Discussion

The Michelson-Morley experiment, first performed in 1887, played a crucial role in shaping modern physics, especially by contributing to Einstein's special theory of relativity. The experiment's null result, demonstrating the independence of light speed from the observer's motion and revolutionizing our understanding of space and time (Manley, 2023; Roy, 2017). The theoretical foundation of the experiment was rooted in the concept of the luminiferous ether, a hypothesized medium through which light waves were believed to propagate. According to this theory, the speed of light should vary depending on Earth's motion relative to the ether, much like the speed of sound varies with the movement of its medium (Abreu & Guerra, 2007; Croca et al., 2019). This study aimed to build upon the historical significance of the experiment by developing a VR simulation to enhance physics education. By offering an interactive platform that enables students to engage with the Michelson-Morley interferometer experiment, the VR tool addresses traditional classroom limitations, including the high cost of equipment and complex alignment procedures (Pathare & Kurmude, 2016).

The validation process confirmed that the VR prototype effectively simulates the theoretical principles underlying the Michelson-Morley experiment. The experts unanimously rated the accuracy of the VR tool at 5.00, indicating high confidence in its ability to replicate the key aspects of light interference and wave propagation. The tool effectively enabled users to visualize interference patterns produced by different lasers, clearly demonstrating the experiment's sensitivity to changes in variables such as beam splitter orientation and mirror angles.

The immersive nature of VR significantly boosted student engagement, reflected by the perfect educational effectiveness score of 5.00. The ability to manipulate experimental variables in real-time facilitated deeper conceptual understanding, which aligns with previous studies that emphasized the benefits of hands-on interaction in virtual environments (Croca et al., 2019; Al-said et al., 2024;

Bancong, 2024). Unlike traditional textbook-based learning, the VR tool offered an experiential approach, enabling students to directly observe the outcomes of their adjustments to the experimental setup, helping them grasp abstract concepts more intuitively (Husnaini & Chen, 2019; Price & Price-Mohr, 2019; Kersting et al., 2021).

Although the VR tool was deemed user-friendly, with a mean navigation score of 4.33, some minor interface improvements could further enhance usability. These included enhancing intuitive controls and providing clearer visual cues to assist novice users. Such refinements would make the VR tool more accessible, especially for students or educators less familiar with virtual environments. Nevertheless, the overall user experience was positive with the interactive features highly rated for promoting active learning.

Physical safety was a notable area for improvement, particularly concerning the potential for motion sickness during extended use of the VR system. The relatively low score of 3.33 in this category indicates that some users, especially those unfamiliar with VR, might experience discomfort. Future iterations of the tool could reduce these effects by incorporating options that let users control the interaction pace, such as slowing movements or reducing visual complexity during demanding tasks. Additionally, while the VR prototype proved educationally beneficial, the cost of implementation and maintenance was flagged as a potential barrier for widespread adoption. The mean score of 3.33 for cost analysis reflects concerns over the financial feasibility of adopting VR technology in institutions with limited budgets. Exploring more cost-effective solutions, such as developing scalable tool versions or integrating them with existing educational platforms, could help broaden its accessibility to a wider range of schools and universities (Pathare & Kurmude, 2016; Bancong et al., 2023).

The successful validation of this VR prototype paves the way for developing similar tools for other historically significant physics experiments, offering new avenues for immersive learning. By addressing the technical and financial limitations highlighted in this study, VR could become a core component of modern physics education. Future work should focus on expanding the scope of the VR simulation to encompass more complex phenomena, including relativistic effects and quantum mechanics. Additionally, long-term studies on the impact of VR-based learning regarding student retention and conceptual understanding would help refine the tool's educational impact.

6. Conclusion

This study successfully developed and validated a VR prototype to simulate the Michelson-Morley interferometer experiment, providing an innovative approach to overcoming traditional challenges in physics education. The validation process, involving three experts with backgrounds in experimental physics and educational practice, revealed that the VR prototype achieved an average validator score of 4.27. The highest-rated indicators (score 5) were the accuracy of the VR simulation in representing the Michelson-Morley experiment, the effectiveness of VR in helping students understand the concept of light interference, and the alignment of VR content with the physics curriculum and learning objectives. These findings underscore the prototype's potential as a powerful educational tool to enhance students' understanding of fundamental physics concepts. By enabling real-time manipulation of experimental variables, such as mirror angles and laser types, the VR tool provided an immersive and interactive platform that closes the gap between theoretical learning and practical experimentation.

However, the study recognizes several limitations. Some users experienced motion sickness during prolonged VR use, highlighting a need for enhanced comfort through interface refinements and customizable settings. Additionally, the high cost of implementing VR systems, including hardware and software requirements, presents a barrier to widespread adoption, particularly for institutions with limited budgets.

Future research should explore cost-reduction strategies, such as scalable VR solutions or integration with existing educational technologies, to increase accessibility. Longitudinal studies are also recommended to assess the long-term educational impact of VR-based learning, particularly in knowledge retention and conceptual understanding. Expanding the scope of VR simulations to include other complex physics experiments could further enrich the educational experience. Practical recommendations include integrating VR tools into the physics curriculum and providing comprehensive training for educators to maximize the effectiveness of this technology. This study demonstrates the significant potential of VR to transform physics education by making complex experiments more accessible, engaging, and impactful, paving the way for broader implementation in academic settings globally.

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