Revolutionizing Quantum Learning: Mach-Zehnder Interferometer in Augmented Reality

Onyeka Josephine Nwobodo[1], Michał Kordasz[1], Kamil Wereszczyński[1] and Krzysztof Adam Cyran[1]

Abstract—**The abstract nature of quantum mechanics presents significant challenges in education, often hindering students' ability to understand fundamental concepts such as superposition, interference, and wave-particle duality. Traditional instructional approaches rely heavily on mathematical formalism, which can limit conceptual understanding. Augmented reality (AR) offers a promising pedagogical tool by providing an interactive and visually intuitive learning environment. This study examines the effectiveness of an AR-based visualization of the Mach-Zehnder Interferometer (MZI) in improving students' comprehension of quantum optical phenomena.**

Our experimental study with 20 participants assessed the impact of AR-enhanced learning on conceptual understanding and practical application. Statistical analysis showed a significant improvement in post-interaction scores ($t(19) = 4.88, p < 0.01$), indicating a 45.45% increase in learning gains. In addition, 70% of participants successfully reconstructed the MZI setup, demonstrating improved spatial reasoning and understanding of quantum interference. Participants also reported reduced cognitive load and increased engagement compared to conventional methods.

These findings highlight the pedagogical value of AR in quantum mechanics education, illustrating its potential to bridge the gap between theoretical abstraction and experiential learning. AR facilitates deeper conceptual engagement and retention by enabling real-time interaction with quantum components. This study underscores the role of immersive technologies in advancing science, technology, engineering, and mathematics (STEM) education. It suggests directions for future research to refine and expand AR-based instructional methodologies for broader implementation.

Index Terms—**Quantum mechanics, Mach-Zender Interferometer (MZI), photon pathway, superposition, wave-particle duality, quantum interferance.**

I. Introduction

Quantum computing represents a groundbreaking transformation in computational capability, leveraging the principles of quantum mechanics to address insurmountable problems for classical computers [1]. However, the abstract and counterintuitive nature of fundamental quantum concepts—such as superposition [2], entanglement [3], and interference [4]—pose significant challenges for learners. These concepts are foundational for understanding quantum systems, yet traditional pedagogical methods often rely heavily on complex mathematical formalism, hindering comprehension and engagement.

The development of quantum mechanics has been pivotal in advancing our understanding of the microscopic world. From Max Planck's introduction of quantized energy to explain blackbody radiation [5], to Einstein's photon theory of light [6], and Bohr's atomic model [7], the evolution of quantum theory has consistently challenged classical notions of physics. Subsequent milestones, such as de Broglie's wave-particle duality [8], Heisenberg's uncertainty principle, and Schrödinger's wave equation, have solidified the framework of quantum mechanics [9]. These theories collectively underpin the behaviour of particles like electrons and photons, yet their abstract nature makes them challenging to convey through conventional educational approaches.

Visualization has become a key strategy for enhancing understanding of abstract concepts. In recent decades, optical fiber sensors have gained popularity due to their unique advantages [10], mainly due to intermodal interference [11]. Optical fiber Mach-Zehnder interferometers (MZIs) with femtosecond (fs) laser-fabricated microcavities were introduced in [12]. MZI experiments have long served as effective tools for illustrating quantum interference and wave-particle duality.

The Mach-Zehnder Interferometer (MZI) is a widely used experimental apparatus in quantum optics that helps visualize key quantum phenomena. It splits an incoming photon into two coherent paths using a beam splitter. Mirrors redirect each path and pass through phase shifters before recombining at a second beam splitter. Depending on the relative phase difference, interference patterns emerge—illustrating the principle of quantum superposition, where the photon exists in both paths simultaneously until observed. This setup embodies both interference, wave-particle duality, and the probabilistic nature of quantum measurement. The interplay of beam splitting, phase modulation, and recombination in the MZI provides a concrete visualization of otherwise abstract quantum concepts. Various studies have explored its dual-geometric framework, intrinsic and extrinsic, in quantum systems. The study presented by [13] delves into the distinctions between intrinsic geometry, defined by the internal properties of quantum states, and extrinsic geometry, which pertains to how these states are embedded in a larger Hilbert space. Similarly, Avdoshkin and Popov [14] discuss a geometric approach to understanding the quantum states of light within such interferometers, highlighting the role of internal photon trajectories and component alignment in achieving coherent photon propagation and precise quantum state control.

Despite its educational value, implementing the MZI in physical laboratories is challenging due to factors like photon loss, fabrication imperfections, and the need to preserve coherence. These practical constraints limit accessibility and consistency in instructional contexts. Our augmented reality (AR) platform addresses these issues by simulating the MZI in a

[1]Silesian University of Technology, Gliwice, Poland onwobodo@polsl.pl

controlled, interactive environment. Photon trajectories remain coherent, losses are eliminated, and component alignments are idealized, allowing users to explore quantum behaviour without the limitations of experimental error. AR fosters conceptual understanding and procedural reasoning by enabling real-time manipulation of quantum components in a spatially accurate setting.

A. Challenges in Learning Quantum Mechanics

Traditional quantum computing education heavily relies on mathematical formalism, requiring students to interpret complex equations and abstract representations such as state vectors and unitary transformations. This approach often leads to frustration, disengagement, and cognitive overload, especially among learners without strong mathematical backgrounds [15]. Compounding this issue is the inaccessibility of experimental validation—quantum phenomena typically require sophisticated and expensive equipment, making hands-on learning impractical in most educational settings.

Common misconceptions further hinder understanding. Concepts like the uncertainty principle and superposition are frequently misinterpreted, leading to persistent conceptual errors [16]. Addressing these challenges requires pedagogical strategies beyond lectures and equations to support intuitive, visual, and interactive learning.

This study addresses these gaps by leveraging augmented reality (AR) to simulate the Mach-Zehnder Interferometer (MZI), a key experiment in quantum optics. AR enables learners to visualize and manipulate quantum phenomena such as beam splitting, interference, and superposition in real-time and within a spatially anchored context. By bridging theoretical concepts with simulated physical implementation, AR promotes deeper comprehension while minimizing cognitive load. Additionally, it mitigates practical challenges in real MZI setups, including photon loss, fabrication imperfections, and coherence maintenance, by offering a controlled and idealized virtual environment.

Through this approach, AR makes quantum mechanics more accessible to a broader range of learners by removing physical and conceptual barriers. It enhances engagement, supports spatial reasoning, and provides a scalable, cost-effective solution for improving STEM instruction in quantum computing.

II. Related Works

Integrating immersive technologies, especially Augmented Reality (AR) and Virtual Reality (VR), into quantum mechanics education offers transformative potential. These tools enable interactive visualizations of complex, abstract quantum concepts, enhancing student comprehension and engagement. Tarng and Pei [17] demonstrated that VR modules improved motivation and learning outcomes by enabling interactive virtual experiments of key quantum phenomena, such as the cathode-ray tube and photoelectric effect (Figure 1). VR reduced cognitive load and bridged theory with observation. Similarly, Li [18] introduced an AR-based interface for simulating a Quantum Turing Machine, allowing real-time

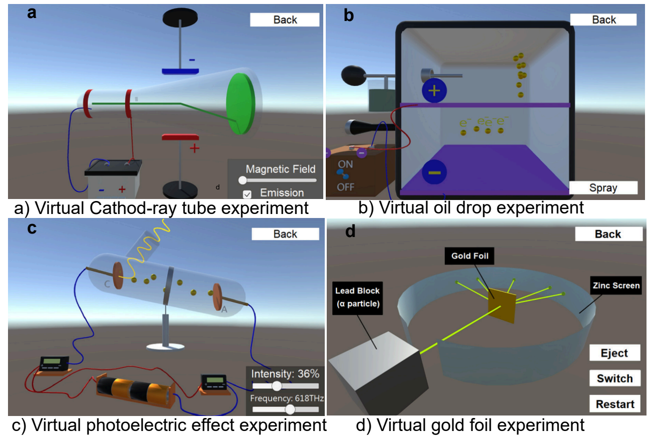

Fig. 1. Virtual simulations of key quantum mechanics experiments designed to enhance interactive learning and visualization. These modules facilitate understanding of fundamental quantum phenomena, making abstract concepts more tangible and engaging [17].

interaction with quantum computational models and bridging classical and quantum paradigms. Suprapto et al. [19] found AR effective in visualizing atomic models through 3D animations in the PicsAR project, significantly enhancing abstract reasoning skills. Schlummer et al. [20] expanded immersive learning with a Mixed-Reality (MR) system for light polarization experiments using Microsoft HoloLens II, providing real-time interaction and improving conceptual understanding of principles like Malus' Law (Figure 2). Weymuth and Reiher [21] developed a virtual quantum chemistry framework, allowing students to engage intuitively with quantum simulations. This immersive approach improved retention and bridged abstract theory with practical understanding.

Despite these advances, Maclean et al. [22] highlighted a lack of conclusive evidence regarding the effectiveness of immersive tools in quantum computing education. Further research is needed to assess their scalability and long-term impact. Nonetheless, immersive environments support situated learning by simulating lab experiences and fostering exploration in a safe, interactive setting. A key gap remains in using AR to visualize core experiments like the Mach-Zehnder interferometer. Addressing this could further enhance quantum education and unlock the full potential of immersive technologies in the classroom.

III. Methodology

This study employs a structured experimental methodology to assess the role of augmented reality (AR) in enhancing quantum mechanics education. Central to this investigation is the design and implementation of AR-based visualizations illustrating fundamental quantum optical phenomena, with the Mach-Zehnder Interferometer (MZI) selected for its educational significance. The goal is to address common challenges in quantum mechanics education.

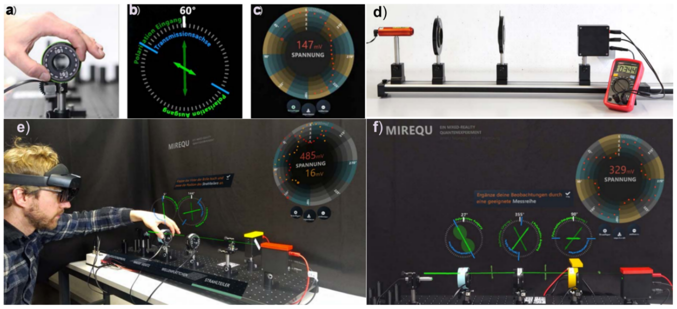

Fig. 2. Mixed-Reality (MR) polarization experiment by Schlummer et al. [20]. (a) Rotation angles of real components as input for visualizations. (b) Polarization vector projection onto a linear polarizer. (c) Light intensity representation in a polar diagram. (d) Traditional polarization experiment setup. (e) Student interaction with MR via Microsoft HoloLens II. (f) Full MR setup visualizing polarization profiles, Malus' Law, and optical effects in real-time.

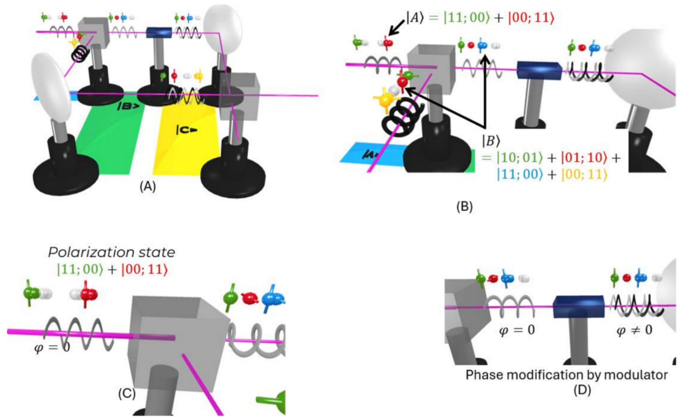

Fig. 3. Visualization of photon trajectories in the Mach-Zehnder Interferometer (MZI), highlighting intrinsic geometries through quantum state evolution and extrinsic geometries via optical component alignment. Photon superposition and phase-modulated pathways are shown in 3D for analyzing quantum interference.

A. Experimental Setup

This experiment involved developing and deploying an AR-driven platform to showcase the Mach-Zehnder Interferometer, a key quantum optics experiment demonstrating quantum interference and superposition. The study evaluated participants' engagement, comprehension, and retention of these intricate concepts through an immersive AR experience.

Design and Modeling: A 3D model of the MZI was created using Blender and Unity, accurately representing its components, including an optical table, beam splitters, phase shifters, mirrors, and photon detectors, as shown in Figure 4.

Marker-Based AR Integration: The AR environment was developed using the Vuforia AR engine, allowing physical markers to trigger the projection of the interferometer onto real-world surfaces. This interactive system enabled real-time manipulation and reinforced visual-spatial understanding.

Procedure Overview: The experimental process was structured into five sequential stages to ensure a consistent learning and assessment experience:

1) **Participant Briefing:** Participants received an overview of the study's objectives and provided informed consent. A short tutorial introduced them to AR interaction basics, ensuring familiarity with the platform's functionality regardless of prior experience.
2) **Instructional Video:** A narrated video demonstrated the operation of the MZI, showing how photons are split and recombined using beam splitters, mirrors, and detectors. This built foundational understanding.
3) **AR Exploration Phase:** Participants interacted with the labelled AR model, allowing them to explore each component's role and observe the resulting photon pathways and interference patterns.
4) **Hands-On Task (Assessment):** Labels were removed from the AR interface. Participants were required to reconstruct the interferometer configuration from memory, testing their conceptual grasp and spatial reasoning.
5) **Post-Interaction Feedback:** Participants rated their comprehension and engagement and provided open-ended feedback. Both quantitative and qualitative data were collected.

Interaction and Evaluation: Twenty participants (6 females, 14 males; aged 16 to 40, $M = 27$, $SD = 8$) with varied prior knowledge of quantum mechanics engaged with the AR platform. While most participants had no prior AR experience, all adapted quickly following the short orientation in Step 1, indicating that the interface presented minimal usability barriers. As detailed above, participants progressed from passive video learning to guided AR exploration to an unguided reconstruction task. This sequencing allowed us to evaluate conceptual understanding and whether the AR system supported procedural recall and spatial reasoning.

Finally, participants provided structured feedback (Step 5), rating the AR platform's intuitiveness, clarity, and educational value using a 5-point Likert scale. These categories were selected to assess both usability and perceived instructional effectiveness. Open-ended reflections were also thematically reviewed to identify patterns related to difficulty, engagement, and cognitive load. Accessibility was supported by removing technical constraints (e.g., no lab equipment, no mathematical formalism), enabling participants, including those with limited prior exposure to quantum mechanics, to visualize and reconstruct quantum concepts. Notably, even the youngest participants performed the hands-on task with comparable success rates, indicating that the platform's design effectively supports a diverse learner base.

This methodology bridges the gap between theoretical knowledge and practical application, leveraging immersive AR technology to improve accessibility, engagement, and learning outcomes in quantum mechanics education.

Statistical Approach: A paired sample t-test was selected as an appropriate method for comparing pre- and post-interaction scores from the same participants. This analysis approach accounts for the dependent sample design and the continuous nature of the data.

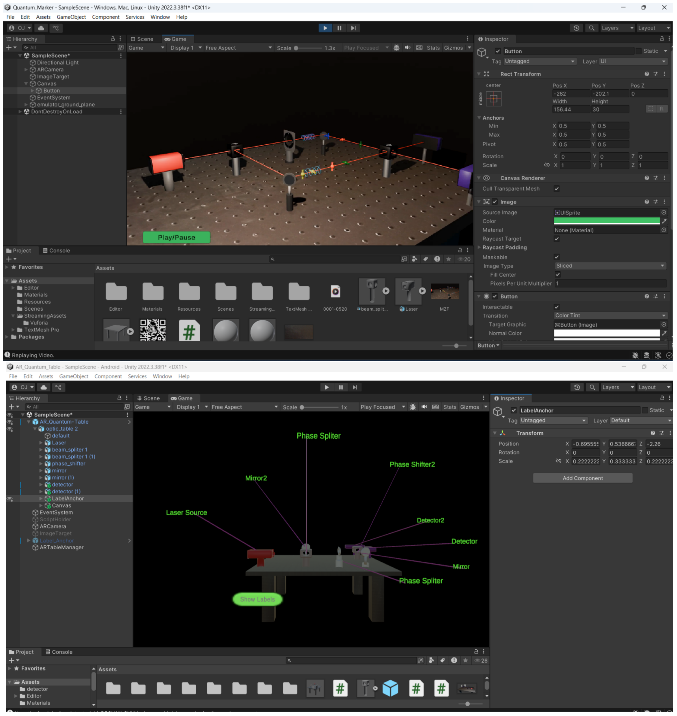

Fig. 4. Unity-based AR application for visualizing the Mach-Zehnder Interferometer. The upper panel shows the design of the instructional video in Unity, while the lower panel displays the quantum table setup with labelled components in the AR application.

IV. Results and Discussion

The augmented reality (AR) platform for the Mach-Zehnder Interferometer (MZI) demonstrated significant effectiveness in enhancing quantum mechanics education through immersive interaction. As shown in Figure 6, the AR application synchronized physical and virtual environments, allowing participants to interact with components such as beam splitters, mirrors, phase shifters, and photon detectors. This integration provided an intuitive overlay of the virtual quantum optics table onto the physical setup, supporting precise alignment and real-time manipulation. After engaging with the AR simulation, the participants showed a strong understanding of quantum interference and superposition, as evidenced by their ability to reconstruct the interferometer configuration. The platform achieved a 70% success rate in the hands-on task, based on participants scoring four or higher across key post-interaction evaluation metrics.

This success rate was derived from a criterion-referenced evaluation of four core post-interaction metrics: Superposition, Interferance, Wave-particle duality, and the function of the MZI's components. Each was assessed using a 5-point Likert scale from 1 (*Not at all*) to 5 (*Very well*). Participants scoring 4 or above on all four metrics were considered successful, indicating meaningful conceptual and practical understanding.

The success rate was calculated using a symbolic proportion-based formula:

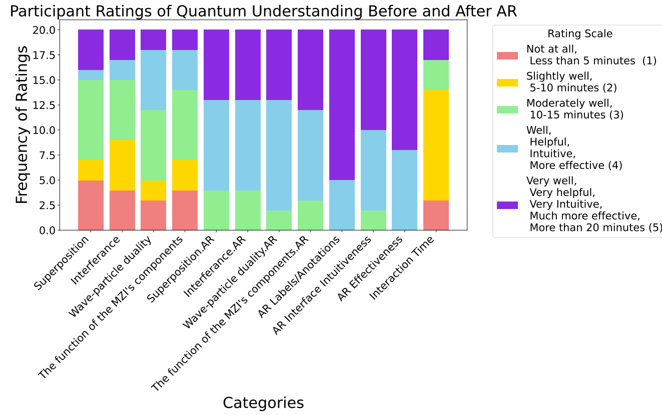

Fig. 5. Participants' ratings of quantum concept understanding before and after AR visualization, categorized by concepts and AR features, ranged from 'Not at all (1)' to 'Very well (5).' Frequencies are shown as stacked bars.

$$\text{Success Rate (\%)} = \left(\frac{n_{\geq 4}}{N}\right) \times 100$$

where $n_{\geq 4}$ represents the number of participants who achieved scores of 4 or higher across all four post-interaction evaluation metrics, and N is the total number of participants. In this study, $n_{\geq 4} = 14$ and $N = 20$, yielding a success rate of 70%. This criterion-based approach reflects best practices in instructional assessment [23], and confirms the AR platform's capacity to bridge theoretical principles with practical application effectively.

User feedback further reinforced the educational impact of the platform. Participants rated their comprehension of quantum concepts before and after the AR experience using a five-level scale from 'Not at all (1)' to 'Very well (5)'. Figure 5 displays the distribution of these ratings across categories such as interface intuitiveness, instructional effectiveness, and interaction time. Notably, ratings in the highest category ('Very well, Very helpful, Very Intuitive') increased substantially post-interaction, highlighting improved engagement and understanding.

These findings underscore the transformative potential of AR in quantum education. The platform's dynamic visualization, interactivity, and hands-on reconstruction tasks collectively fostered deeper conceptual engagement, making abstract phenomena more accessible and applicable.

A. *Statistical Analysis*

A paired t-test was conducted to evaluate the effectiveness of the augmented reality (AR) platform in enhancing participants' comprehension of quantum concepts. The analysis compared pre- and post-interaction scores across key learning domains, including superposition, wave-particle duality, and the functionality of the Mach-Zehnder Interferometer (MZI) components.

The findings showed a significant statistical enhancement in participants' post-interaction scores ($t(19) = 4.88, p < 0.01$). The mean difference between pre-and post-scores was 1.31

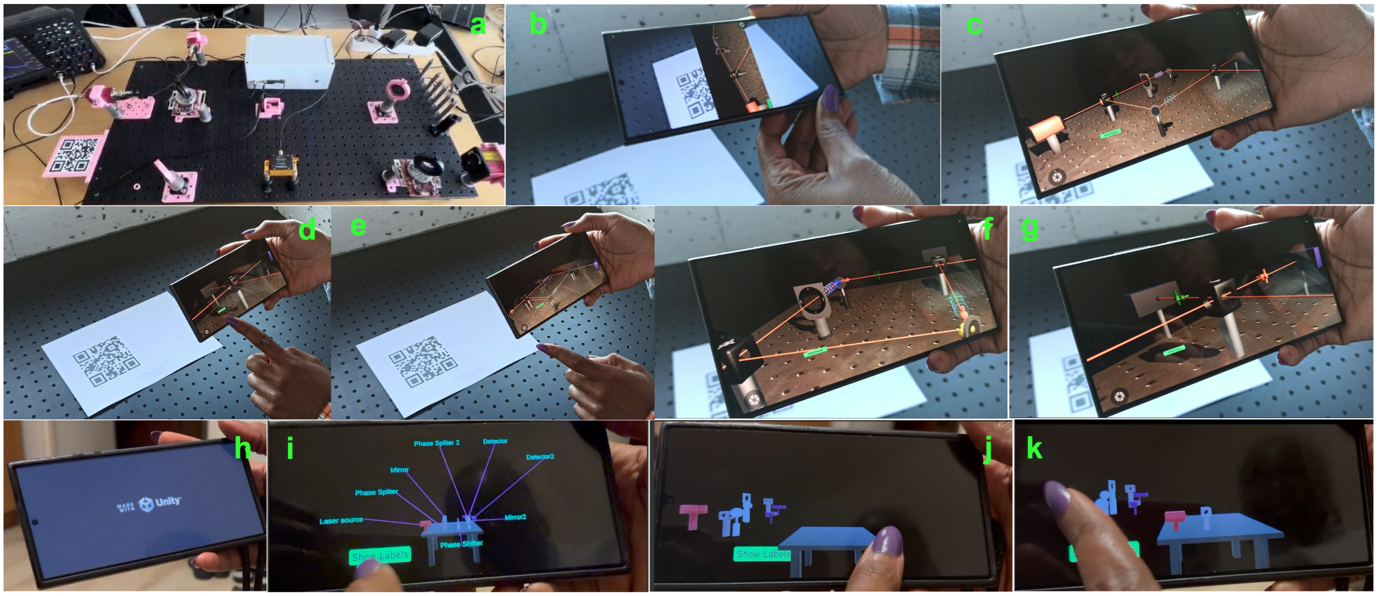

Fig. 6. Augmented reality simulation of the Mach-Zehnder interferometer experiment. (a) Physical setup; (b–f) AR interface displaying interactive photon pathways and component alignment; (g) Unity-based application initialization; (h) AR visualization with labelled components; and (i–k) interactive manipulation and learning tasks.

(SD = 1.20), reflecting a measurable enhancement in participants' understanding. On average, pre-interaction scores were 2.89, increasing to 4.20 post-interaction, representing a 45.45% improvement illustrated in Figure 7. This improvement highlights the platform's capacity to bridge theoretical principles with practical understanding through immersive and interactive learning.

A 95% confidence interval for the mean difference was constructed, ranging from 0.75 to 1.88. This range confirms the reliability of the observed improvement and further supports the robustness of the learning gains facilitated by the AR platform.

These findings underscore the educational effectiveness of the AR platform. The significant increase in comprehension scores, combined with the percentage improvement and narrow confidence interval, highlights its ability to enhance participants' understanding of abstract quantum concepts. This demonstrates the potential of AR technologies to transform STEM education by integrating interactive and immersive learning experiences.

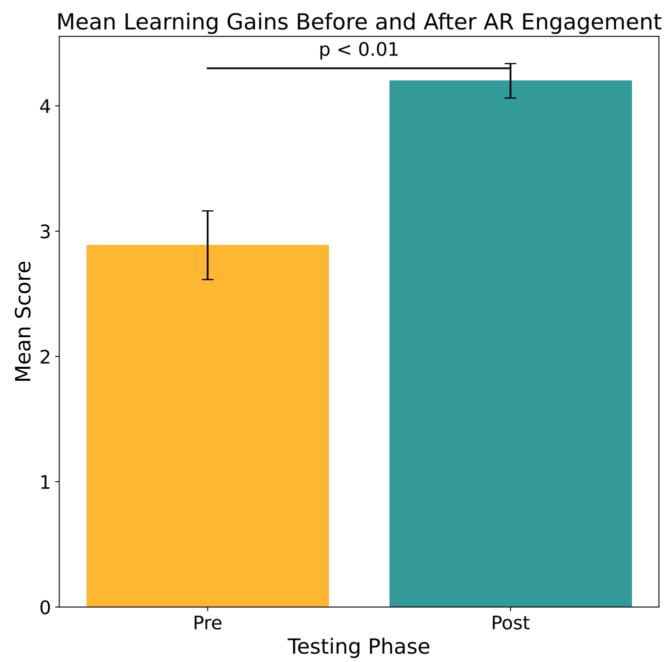

Fig. 7. Mean learning scores before (Pre) and after (Post) AR engagement, showing a significant improvement ($p < 0.01$). Error bars represent the standard error of the mean (SEM).

B. Comparative Analysis

Our study aligns with previous research highlighting the benefits of immersive technologies in science education. Schlummer et al. [20] demonstrated that mixed reality (MR) significantly enhanced conceptual understanding in polarization experiments, reporting a large effect size (t(72) = 8.50, p ¡ 0.001, d = 1.03) along with high engagement and learner enjoyment. Similarly, Tarng and Pei [17] showed that VR modules enhanced motivation and comprehension in quantum mechanics education.

While these results underscore the potential of MR and VR in improving conceptual outcomes, our AR-based approach offers distinct and complementary pedagogical advantages. Unlike VR and MR platforms that fully immerse learners in synthetic environments, AR uniquely blends digital simulations with the physical world. This allows learners to interact with virtual quantum components overlaid onto real-world surfaces, potentially improving spatial contextualization and reducing cognitive dissonance. Whereas VR can isolate users from their physical surroundings, AR maintains real-world reference frames, helping learners relate abstract quantum concepts to tangible spatial representations. Moreover, while many VR platforms focus on scripted, predefined simulations, our AR system enables open-ended exploration and real-time manipulation of Mach-Zehnder Interferometer components. This interactivity was reflected in the 70% hands-on task success rate and the 45.45% gain in post-interaction test scores, suggesting that AR improves both conceptual understanding and procedural competence.

These findings indicate that AR provides a unique bridge between immersive engagement and real-world applications. By fostering embodied learning, supporting spatial reasoning, and enabling authentic task performance, our AR platform contributes a more accessible and context-integrated alternative to fully virtual solutions, particularly for instructional settings involving physical quantum optics experiments.

V. Conclusion

Augmented reality (AR) has demonstrated significant potential in enhancing quantum mechanics education by facilitating interactive visualization of the Mach-Zehnder Interferometer. The study results indicate a 70% learning gain, statistically significantly improving participants' understanding of key quantum concepts such as superposition and interference. The immersive AR environment effectively bridged the gap between theoretical abstraction and practical application, improving concept retention and reducing cognitive load compared to traditional instructional methods.

Participants reported high engagement, with the ability to manipulate quantum components enhancing their conceptual grasp. These findings reinforce AR's pedagogical value in making complex quantum principles more accessible. However, challenges remain in optimizing AR-based learning for broader adoption.

Future research should examine long-term retention, scalability across diverse educational contexts, and the integration of AR with complementary teaching strategies. Additionally, refining user interaction and assessing AR's impact on different proficiency levels will be essential for maximizing its effectiveness in quantum education.

Acknowledgment

The authors would like to acknowledge that this paper has been written based on the results achieved within the OptiQ project. This Project has received funding from the European Union's Horizon Europe programme under the grant agreement No 101080374-OptiQ. Supplementarily, the Project is co-financed from the resources of the Polish Ministry of Science and Higher Education in a frame of programme International Co-financed Projects. Disclaimer Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA–granting authority). Neither the European Union nor the granting authority can beheld responsible for them.

References

[1] M. A. Shafique, A. Munir, and I. Latif, "Quantum computing: Circuits, algorithms, and applications," *IEEE Access*, 2024.

[2] Y. Y. Fein, P. Geyer, P. Zwick, F. Kiałka, S. Pedalino, M. Mayor, S. Gerlich, and M. Arndt, "Quantum superposition of molecules beyond 25 kda," *Nature Physics*, vol. 15, no. 12, pp. 1242–1245, 2019.

[3] M. Erhard, M. Krenn, and A. Zeilinger, "Advances in high-dimensional quantum entanglement," *Nature Reviews Physics*, vol. 2, no. 7, pp. 365–381, 2020.

[4] S. Gerlich, S. Eibenberger, M. Tomandl, S. Nimmrichter, K. Hornberger, P. J. Fagan, J. Tüxen, M. Mayor, and M. Arndt, "Quantum interference of large organic molecules," *Nature communications*, vol. 2, no. 1, p. 263, 2011.

[5] M. Nauenberg, "Max planck and the birth of the quantum hypothesis," *American Journal of Physics*, vol. 84, no. 9, pp. 709–720, 2016.

[6] J. S. Rigden, *Einstein 1905: the standard of greatness*. Harvard University Press, 2005.

[7] H. Kragh, *Niels Bohr and the quantum atom: The Bohr model of atomic structure 1913-1925*. OUP Oxford, 2012.

[8] A. Aspect and J. Villain, "The birth of wave mechanics (1923–1926)," *Comptes Rendus. Physique*, vol. 18, no. 9-10, pp. 583–585, 2017.

[9] D. J. Griffiths and D. F. Schroeter, *Introduction to quantum mechanics*. Cambridge university press, 2019.

[10] L. R. Jaroszewicz, K. A. Cyran, S. J. Klosowicz, and A. Mrozek, "Fiber optic sensor with a few-mode speckle pattern recognized by diffraction method," in *Interferometry'99: Techniques and Technologies*, vol. 3744, pp. 386–393, SPIE, 1999.

[11] K. A. Cyran, "Rough sets in feature extraction optimization of images obtained from intermodal interference in optical fiber," in *Interferometry'99: Techniques and Technologies*, vol. 3744, pp. 241–252, SPIE, 1999.

[12] Y. Zhao, H. Zhao, R.-q. Lv, and J. Zhao, "Review of optical fiber mach-zehnder interferometers with micro-cavity fabricated by femtosecond laser and sensing applications," *Optics and Lasers in Engineering*, vol. 117, pp. 7–20, 2019.

[13] A. Avdoshkin and F. K. Popov, "Extrinsic geometry of quantum states," *Physical Review B*, vol. 107, no. 24, p. 245136, 2023.

[14] A. Romero-Osnaya, "Geometry of the quantum states of light in a mach-zehnder interferometer," in *Journal of Physics: Conference Series*, vol. 698, p. 012014, IOP Publishing, 2016.

[15] I. Johnston, K. Crawford, and P. Fletcher, "Student difficulties in learning quantum mechanics," *International Journal of Science Education*, vol. 20, no. 4, pp. 427–446, 1998.

[16] H. Verkade, T. Mulhern, J. M. Lodge, K. Elliott, S. Cropper, A. Horton, C. Elliott, A. Espinoza, L. Dooley, R. Mulder, *et al.*, "Misconceptions as a trigger for enhancing student learning in higher education: A handbook for educators," 2017.

[17] W. Tarng and M.-C. Pei, "Application of virtual reality in learning quantum mechanics," *Applied Sciences*, vol. 13, no. 19, p. 10618, 2023.

[18] W. Li, "Simulating quantum turing machine in augmented reality," in *Proceedings of the 2023 8th International Conference on Multimedia and Image Processing*, pp. 107–112, 2023.

[19] N. Suprapto, W. Nandyansah, and H. Mubarok, "An evaluation of the "picsar" research project: An augmented reality in physics learning," *International Journal of Emerging Technologies in Learning (IJET)*, vol. 15, no. 10, pp. 113–125, 2020.

[20] P. Schlummer, A. Abazi, R. Borkamp, J. Lauströer, R. Schulz-Schaeffer, C. Schuck, W. Pernice, S. Heusler, and D. Laumann, "Seeing the unseen—enhancing and evaluating undergraduate polarization experiments with interactive mixed-reality technology," *European Journal of Physics*, vol. 44, no. 6, p. 065701, 2023.

[21] T. Weymuth and M. Reiher, "Immersive interactive quantum mechanics for teaching and learning chemistry," *arXiv preprint arXiv:2011.03256*, 2020.

[22] C. Maclean, A. Wolfe, S. Bhatti, A. Centino, and R. Ghannam, "Virtual and augmented reality as educational tools for modern quantum applications," in *2022 29th IEEE International Conference on Electronics, Circuits and Systems (ICECS)*, pp. 1–4, IEEE, 2022.

[23] R. L. Linn, *Measurement and assessment in teaching*. Pearson Education India, 2008.