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Building a self-guided Virtual Reality learning tool for Electromagnetism

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Prof. Ilie has been recognized as an emerging leader in education by her selection to the Strategic Instructional Innovations Program, to develop Virtual reality (VR) simulations and learning environments to support student learning for electrical engineering courses.

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[WIP]: Building a self-guided Virtual Reality learning tool for Electromagnetism

Abstract

The three-dimensional nature of electromagnetism concepts does not translate well to two-dimensional platforms, making it difficult for students to build intuition about these phenomena in traditional learning settings. Virtual Reality (VR), a simulated three-dimensional environment, offers an immersive, realistic, and interactive 3D environment that enables students to visualize complex concepts and actively manipulate these abstractions.

This paper discusses the development, implementation, and assessment of a self-guided tool designed to teach engineering students the most fundamental concepts in the theory of electromagnetism: Maxwell's equations. The self-guided and adaptable nature of VR-based learning allows students to adjust the difficulty level and control the pace of their progress, enabling them to tackle increasingly complex topics. This personalized approach has the potential to foster a deeper understanding and a sustained interest in the topic.

To assess the tool's efficacy, in-game conceptual quizzes measure students' understanding. Additionally, headset-tracking technology captures user eye-tracking data, providing valuable insights to guide the experience design decisions.

Introduction

College students often face challenges in understanding complex concepts related to the theory of Electromagnetism (E&M). These difficulties primarily stem from the abstract and non-intuitive nature of electromagnetic phenomena, which are invisible and lack a tangible presence in the real world. Traditional teaching methods often rely on passive learning, such as lectures and paper assignments, which fail to actively engage students in the learning process. Moreover, the inherently three-dimensional nature of electromagnetic phenomena does not translate well onto two-dimensional platforms like computer screens or textbooks frequently used in traditional education.

As education embraces innovative methods to overcome these challenges, Virtual Reality (VR) has emerged as a promising tool that creates personalized and immersive learning environments tailored to diverse student needs. VR enables students to immerse themselves in virtual 3D environments where abstract concepts can be visualized and manipulated in real time, making complex ideas more intuitive and accessible[1]. For instance, rather than passively reading about the generation and propagation of electromagnetic waves in a textbook, students can interact with and explore these phenomena in a simulated setting. Studies have demonstrated that integrating VR into education enhances motivation, knowledge retention, and conceptual understanding[2]. This highlights the importance of investigating the potential impact of VR-based learning on educational outcomes and student engagement.

Interest in VR technology has surged dramatically since the 1980s[3], with its educational applications emerging in the 1990s[4]. Early uses of VR in education predominantly targeted the medical field. For example, VR technology was used to simulate the structure and function of the eye, allowing students to observe changes in the iris and pupil by adjusting viewpoints and object positions[5]. Their findings showed that VR significantly enhanced students' engagement, motivation, and comprehension of abstract scientific concepts. Similarly, "Merlin's Playground," a VR environment for electromagnetism education[6], helped students grasp abstract concepts in magnetostatics. These studies highlighted the potential of Virtual Reality as a transformative tool for education, particularly in STEM fields.

Building on these advancements, our research aims to address the specific challenges of teaching electromagnetism through the development of a VR-based, self-guided learning tool. Created using Unity, this tool facilitates the visualizations of abstract electromagnetic phenomena into tangible, interactive experiences. This tool, developed and tested by a group of students at the University of Illinois Urbana-Champaign (UIUC), has been used in an undergraduate Electrical and Computer Engineering (ECE) course since Spring 2021 and continues to be refined based on student feedback and instructional goals.

The VR experience described here introduces students to the concept of *Wave Polarization*, where they can explore a space that resembles the International Space Station, visualize the propagation of electromagnetic waves, and engage in hands-on experiments. Learners also complete in-game quizzes designed to reinforce their understanding. Compared to traditional study methods, VR-based learning allows students to progress at their own pace, providing flexibility for remote learning while fostering deeper engagement[7]. The tool further personalizes the experience by integrating features like real-time interactive wave manipulation that allows the visualization of different waveforms with user specified characteristics. In this study, learners have been surveyed to evaluate their knowledge gain and gather feedback on the VR learning experience.

Despite the growing body of research, there is still a need to explore the integration of VR tools into engineering education, particularly for college-level courses. Our work seeks to fill this gap by developing and evaluating an innovative VR learning tool that facilitates conceptual understanding.

VR Experience: Wave Polarization Experiment

This VR experience introduces the learner to concepts pertaining to *wave polarization*. In order to provide real-life context for the applicability of these concepts, the game environment is designed to resemble the experience of being on the International Space Station (ISS). Figure 1 presents screenshots from the VR application, illustrating the experiment space in panel (a) and the assessment space in panel (b).

The VR experience begins with a voice- and text-narrated tutorial designed to guide learners through the fundamentals of wave polarization and provide guidance on how to interact with the VR environment. The tutorial provides clear, step-by-step instructions on manipulating parameters in the wave equation and visualizing these changes in real time. Each of the wave parameters is described and introduced to the learner along with its representation and function, and the instructions on how to adjust them using the interactive wave parameter panel shown in Figure 2.

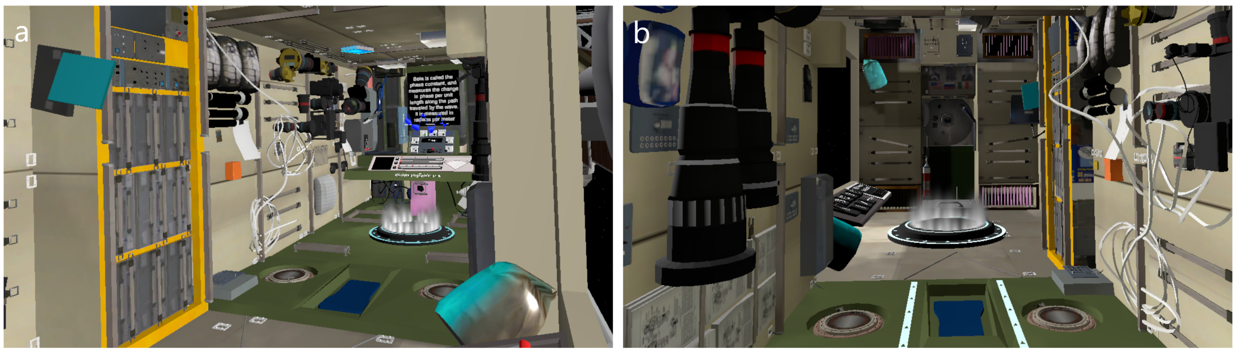

Figure 1: Scenes from the *Wave Polarization* VR experience showing: (a) the set showing the experiment space; (b) the assessment space.

Learners can use the interactive platform to generate EM waves with various characteristics and the corresponding polarization type is displayed on the screen in front of the learner, as shown in Figure 2.b.

Note that for simplicity, the wave equation presented to the learner propagates in the $\pm\hat{\mathbf{z}}$ direction and has components in the $x - y$ plane:

$$\mathbf{E}(\mathbf{z}, t) = \hat{\mathbf{x}} E_x \sin(\omega t - \beta z) + \hat{\mathbf{y}} E_y \sin(\omega t - \beta z - \phi)$$

Learners can adjust three key parameters of the wave:

- **phase constant** β: This measures the change in phase per unit length along the wave's path, allowing learners to visualize how the wavelength impacts the wave's spatial properties.
- **angular frequency** ω : This measures how fast the wave oscillates, demonstrating how frequency affects the wave's temporal behavior.
- **phase** ϕ: This indicates the phase difference between the x and y components of the wave, enabling learners to explore how it alters the wave's polarization state.

In addition to these parameters, learners can also:

- adjust the **propagation direction** to observe how the wave travels in different directions.
- adjust the relative **amplitude of electric field components** E_x **and** E_y, which demonstrates the polarization state of the wave based on its helicity.

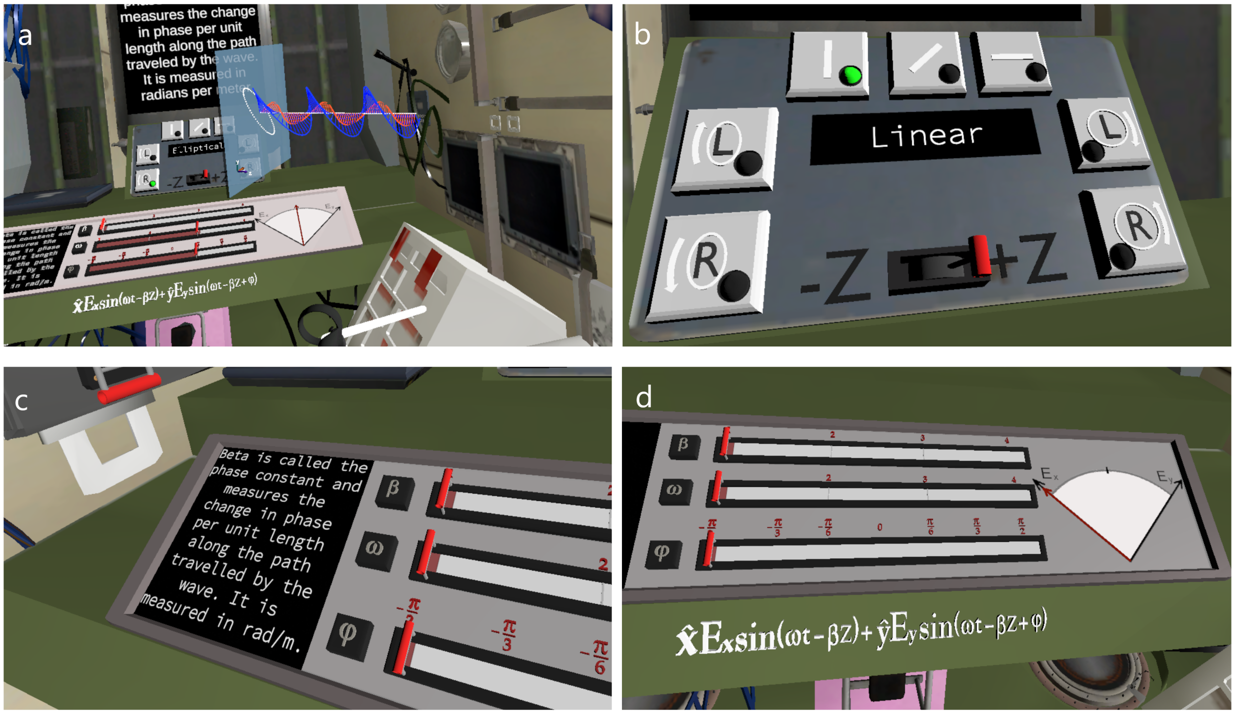

Figure 2: *Wave Polarization* VR experience showing screen captures of: (a) the experiment space; (b) a zoomed in view of the *polarization type* interface; (c) the interactive wave parameter panel showing the β, ω, and ϕ wave parameters selectors and the screen that provides their definitions; (d) the interactive wave parameter panel showing the wave equation and the wave amplitude selector.

- toggle the visualization of **the magnetic field vector**, in addition to visualizing the electric field vector, providing a complete visualization of electromagnetic wave propagation.

To increase engagement and contextualize the learning process, the VR experience also includes items for the learner to discover and interact with during gameplay. For instance, various facts about the International Space Station (ISS) are provided in a *Did you know?* type of interaction, which are connected with existing items in the scene (books, cameras, etc.). This game element is introduced to allow the learner to contextualize their learning experience. Figure 3 shows an example from the *Wave Polarization* VR application.

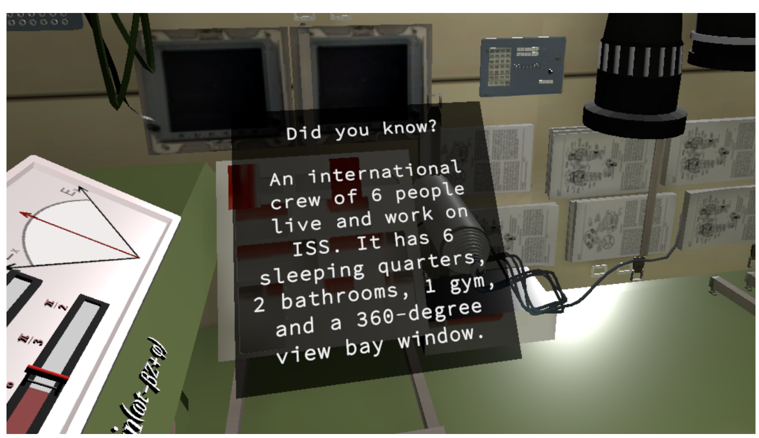

Figure 3: An example of *Did you know?* fact displayed in game in the *Wave Polarization* VR experience.

VR Experience: In-game Assessment

After completing the guided experiment, learners are teleported to another section of the space station (shown in Figure 1.b). Under the pretext of an emergency and the need ("*to save the space station*"), learners must complete a gamified assessment designed to test their understanding of the concepts pertaining to wave polarization. This quiz introduces time pressure (the assessment allotted time is 2 minutes) and incorporates a fail state to increase the challenge and engagement. Learners must match the polarization of five incoming waveforms, which are randomly generated, with the antenna that maximizes the transmitted power. If the learner fails to match five waveforms correctly within 2 minutes, the station's alarm system triggers, and the station experiences a simulated crash. This gamified approach not only tests conceptual understanding but also keeps learners engaged and motivated. Figure 4 shows the assessment space (panel a) and the fail state (panel b).

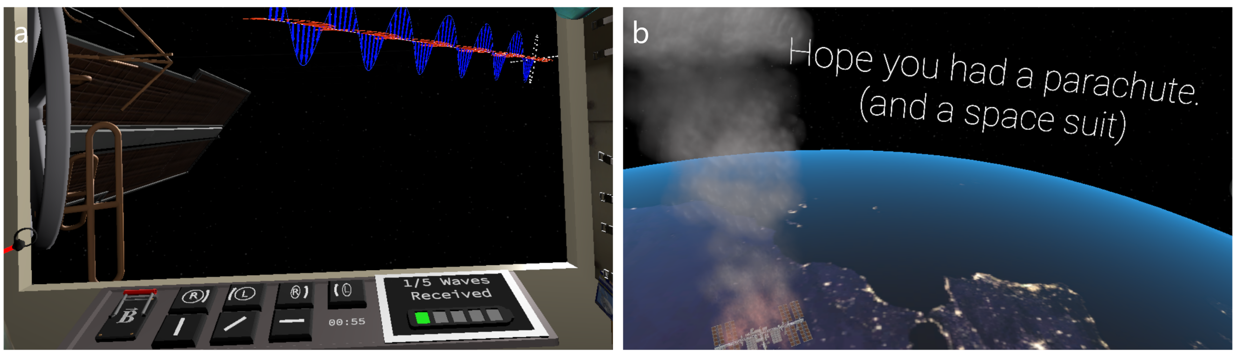

Figure 4: Scenes from the set of the *Wave Polarization* VR experience showing: (a) the in-game assessment space; (b) the fail state

Student Self-Assessment

The electromagnetic VR laboratory course was introduced to complement an existing traditional Electromagnetism lecture course. In the VR laboratory course, students attend one-hour per week sessions under the guidance of a Teaching Assistant (TA). The course covers a series of classic topics in electromagnetism, including Gauss' Law, electrostatic potential, Faraday's Law, Ampere's Law, wave polarization, and more.

After the *Wave Polarization* VR experience was completed, students were administered a self-assessment survey regarding their perception of learning. Figure 5 synthesizes these findings, which show that the VR experience had positive effects on student's perception of their understanding of wave polarization concepts. For instance, when asked whether *Visualizing the changing electric and magnetic fields as the wave propagates helped me better understand the concept of wave polarization*, the majority of participants (71.4%) indicated a significant positive impact ("a great deal" or "a lot"), as shown in Figure 5.a . The remaining 28.6% acknowledged a moderate improvement in understanding, while no participant found the visualization not helpful. These findings indicate that the visualization of electric and magnetic fields was highly effective in aiding participants' comprehension of wave polarization, emphasizing the value of VR for complex scientific visualizations.

In a follow-up question, participants were asked whether the visualization was more helpful in a 3D environment (Figure 5.b). Most participants (71.43%) reported significant benefits from experiencing the experiment in 3D. A smaller proportion (28.57%) found it moderately or slightly

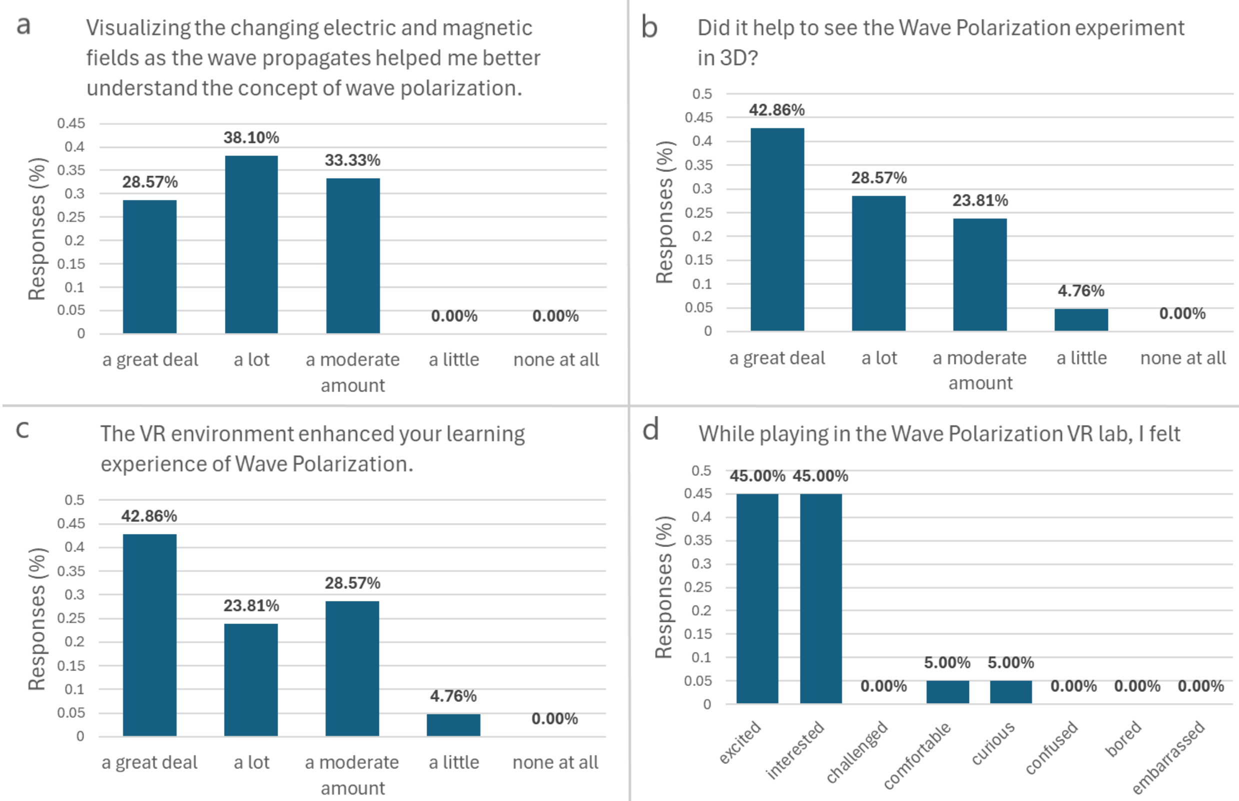

Figure 5: Results from self-assessment survey of student participants

These results demonstrate that the immersive 3D nature of the VR environment enhances both engagement and student's perception of their own understanding, affirming the advantages of VR in creating effective learning experiences.

Figure 5.c presents the survey results regarding the participants' perceptions of the VR environment as a learning medium. When asked whether *the VR environment enhanced their learning experience of Wave Polarization*, most participants (66.7%) indicated that the VR environment significantly enhanced their learning experience, while 28.6% found it moderately beneficial. A minority (4.8%) reported only limited enhancement. Once more, these results suggest that VR can be impactful for improving the learning experience, though variations in user responses point to potential areas for further optimization and customization.

Lastly, Figure 5.d presents the survey results on the participants' emotional responses to the VR experience. The survey collected responses to feelings such as "excited," "interested," "challenged," "comfortable," "curious," "confused," "bored," and "embarrassed." Although it was anticipated that some students who are unfamiliar with VR environments might feel confused or challenged, no participants reported negative emotions. A small percentage indicated feelings of comfort or curiosity, while 90% of participants reported positive emotions such as excitement and interest. These findings suggest that the scene layout and clear tutorial successfully created an engaging and stimulating environment, with participants predominantly experiencing excitement and interest.

Challenges in VR Adoption

Our ultimate goal is to develop a self-guided learning tool that enables students to progress through the material at their own pace and with minimal instructor intervention. To achieve this, we have carefully structured the learning experience with a smooth learning gradient, ensuring that students can gradually acquire the necessary skills without feeling overwhelmed. The VR interface is designed to be intuitive, reducing the cognitive load and allowing students to focus on conceptual learning rather than struggling with the mechanics of VR interaction.

It has been suggested that students unfamiliar with VR technology often experience initial uncertainty, which may result in hesitation or reduced enthusiasm for enrolling in courses that incorporate it[8].

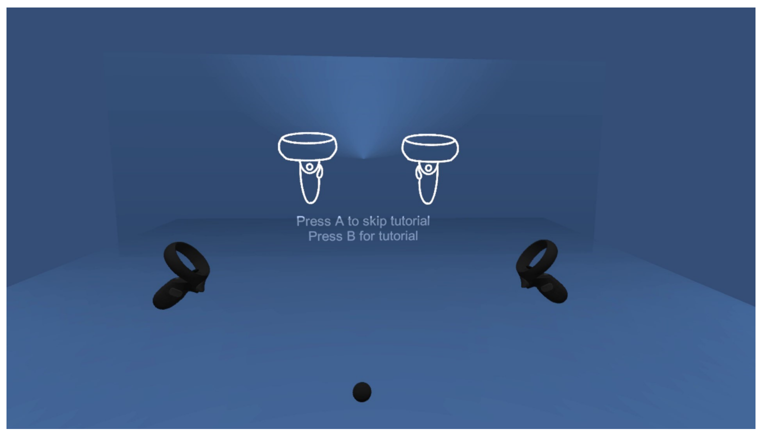

Figure 6: Screen capture from the introductory module that contains a tutorial on the use of VR controller operations.

Therefore, in order to accommodate students who might be unfamiliar with VR devices, we have designed a tutorial to facilitate their smooth transition into using the controllers and the functions that are adopted in the application. Therefore, before starting the VR experience, students are presented with the option to complete this tutorial. Figure 6 shows a screen capture from the tutorial, which introduces them to the functions associated with each of the buttons present on VR controllers. The tutorial also includes simple interactive tasks such as grabbing and dropping objects, allowing students to practice basic VR interactions in an environment without distractions.

The design and development of VR educational tools demands substantial time, resources, and a well-coordinated team. Given that VR is still a relatively new technology, many faculty members may hesitate to adopt it. Therefore, integrating VR-based learning demands modifications in instructional strategies, assessment methods, and faculty training, all of which can present logistical and pedagogical challenges. However, these challenges can be addressed through a structured implementation strategy. Training sessions and technical support can ease the transition, providing instructors with the confidence to integrate VR into their teaching[9]. Additionally, introductory sessions and guided tutorials can help students become more comfortable with the technology, easing their apprehension and encouraging active participation. Institutions can also adopt hybrid models that integrate VR learning tools to complement traditional learning methods, allowing a smoother and more gradual transition rather than an abrupt shift.

Furthermore, funding is a significant consideration for institutions exploring VR adoption. The work presented here was conducted using *Oculus Rift S* PC-powered VR gaming headsets, each averaging around $400[10]. Additionally, each headset requires a dedicated desktop, valued at approximately $5000 in 2019, along with sufficient dedicated physical space for user interaction. These requirements make VR setups costly and space-intensive, limiting the number of students participating in VR-based learning at any given time.

While high-end VR setups can be expensive, universities can explore alternative funding strategies to make adoption more feasible. For instance, shared VR labs and partnerships with industry can help offset costs and provide additional resources[7]. Additionally, historical data[11,12] shows a steady and significant decline in the cost of personal computers and peripheral equipment over the years. This ongoing downward trend suggests that, in the near future, the cost of VR-compatible PCs will become significantly more affordable, reducing the financial barriers to adoption. For instance, the use of currently available standalone VR headsets (such as Meta Quest 3[13]), which do not require a dedicated PC, reduces the hardware costs by one order of magnitude compared to the technology available only five years ago. In addition, these devices significantly alleviate space constraints, making VR adoption more accessible and scalable. Moreover, cloud-based VR platforms could allow students to access VR learning experiences remotely without the need for expensive on-campus facilities[14].

Future Directions

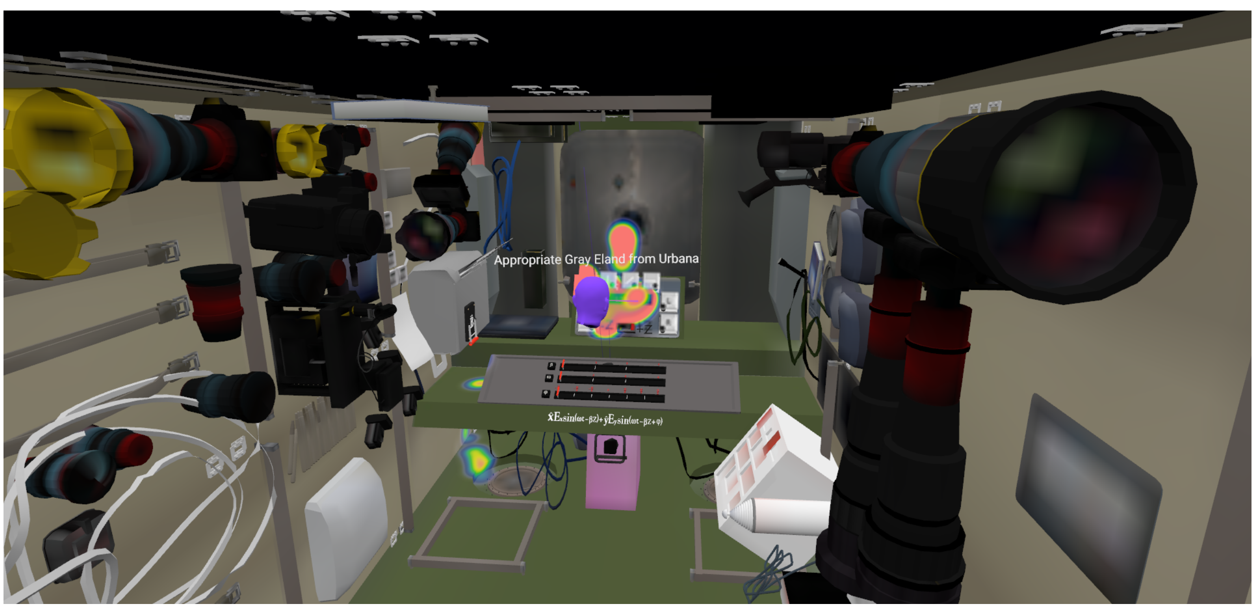

Figure 7: Test implementation of the headset tracking software: the object heatmaps show which areas receive the most attention by overlaying user gaze and eye tracking data.

Headset-tracking software is implemented to log user input while in the VR experience. An

example of the interface is presented in Figure 7. This object heatmap shows which areas receive the most attention by overlaying user gaze and eye-tracking data. The data collected during the VR experience will provide deeper insights into the student's learning, as we will be able to measure how many times an object in the experiment scene has been seen, how long the student gazed at it, the order in which it has been interacted with, how long it took from the start of the session to be seen, etc. For instance, this type of data collection will provide insight into the order in which the quiz questions are answered, which questions require the most guidance from the experiment itself, for how long students engage with the experiment, and where students' attention is being distributed. To date, it is not well understood how concurrent tasks influence students' resource allocation; however, the influence of rewarding alternative tasks is magnified whenever the cognitive load within a task is high[15]. In addition, we are able to deliver questionnaires to students directly within the VR experience and get instant feedback on their learning experience. This enables the team to collect accurate and timely survey responses by minimizing the time between the user experience and the survey administration.
Physics courses, especially Electricity and Magnetism, are fundamental not only for physics students but also for many engineering majors worldwide. Beyond electromagnetism, VR holds significant potential in physics and, therefore, engineering education[16], particularly in areas where students struggle with conceptual understanding. Topics such as quantum mechanics[17], relativity, and microscopic interactions present challenges similar to electromagnetism, as many of their effects cannot be observed directly. Traditional teaching methods often fall short in conveying these abstract concepts effectively, making immersive visualization tools like VR particularly valuable.

The development of a VR module for electromagnetism courses can be extended to enhance the visualization of other complex physical phenomena. The modular design of our existing VR framework for electromagnetism allows for easy adaptation to other disciplines with minimal effort. For instance, medical students without an engineering background often struggle with fundamental physics concepts such as wave propagation, longitudinal and transverse waves, electromagnetism, current, and voltage. However, a solid understanding of these principles is crucial for the next generation of physicians, particularly in the context of point-of-care technology and diagnostic tools. This project lays the groundwork for VR modules that integrate physics concepts into the medical curriculum, helping students grasp essential topics such as wave behavior in different materials, the fundamentals of magnetic fields, and the mechanisms behind magnetic resonance imaging.

Acknowledgments

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