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Evaluating the Impact of Interaction Level on Content Learning in the Eureka VR Environment for Mining Engineering Education

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Abstract

Virtual reality (VR) has increasingly become a popular tool in education and is often compared with traditional teaching methods for its potential to improve learning experiences. However, VR itself holds a wide range of experiences and immersion levels within, from less interactive environments to fully interactive, immersive systems. This study explores the impact of different levels of immersion and interaction within VR on learning outcomes. The project, titled Eureka, focuses on teaching the froth flotation process in mining by comparing two VR modalities: a low-interaction environment that presents information through text and visuals without user engagement, and an immersive, high-interaction environment where users can actively engage with the content. The purpose of this research is to investigate how these varying degrees of immersion affect user performance, engagement, and learning outcomes. The results of a user study involving 12 participants revealed that the high-interaction modality significantly improved task efficiency, with participants completing tasks faster than those of the low-interaction modality. Both modalities were similarly effective in conveying knowledge, as evidenced by comparable assessment scores. However, qualitative feedback highlighted design considerations, such as diverse user preferences for navigation and instructional methods. These findings suggest that, while interactive immersion can improve efficiency, effective VR educational tools must accommodate diverse learning styles and needs. Future work will focus on scaling participant diversity and refining VR design features.

Introduction

Virtual reality (VR) is growing increasingly as a tool applied for education, design, and training, specifically in fields like STEM education and engineering. Virtual reality allows students and professionals to engage in simulations in which they can have hands-on experiments and explore complex concepts and systems, helping them to learn or practice skills that would otherwise be too dangerous or costly to perform in real life. Traditional learning is often limited to textbooks and lectures. However, VR helps students engage in an immersive environment and therefore can help them better grasp the ideas and concepts being taught to them [2].

The COVID-19 pandemic further highlighted the potential of VR in education, as institutions looked for alternatives to in person learning. Immersive technologies provided effective replacements for hands-on experiences, particularly in fields such as science, engineering, and medicine ([21]. Research during this period demonstrated the value of VR in improving engagement and learning outcomes, especially in technical disciplines. Advances in mobile platforms, network capabilities, and wearable devices have since increased VR accessibility, making it a feasible tool for a wide range of educational applications.

Despite its growing use, VR is not a uniform medium. It encompasses a spectrum of experiences, from less interactive environments that present information passively to highly interactive systems that require active engagement [19]. Understanding how these varying levels of immersion affect learning outcomes is important for designing effective VR-based educational tools.

This study investigates the role of immersion and interaction levels in VR on learning outcomes, specifically within mining engineering education. Conducted as part of the Eureka project, it focuses on teaching the froth flotation process by comparing two VR modalities: a less interactive environment presenting content through text and visuals, and an immersive, high-interaction environment that allows users to manipulate and engage with the content.

This paper makes the following contributions:

1. Highlighting the need for a systematic framework to compare interaction levels in VR environments, offering a foundation for studying their impact on learning outcomes in technical education.
2. Identifying the variability in individual learning styles and VR usage, and the importance of accounting for this diversity in educational tool design and product audience.
3. Offering preliminary design principles for developing effective VR educational tools, focusing on balancing interaction levels to enhance user engagement and knowledge retention.

The findings aim to contribute to VR education by identifying design elements that enhance learning outcomes and user engagement. The results provide evidence-based recommendations for optimizing VR-based tools, particularly for technical subjects that require hands-on or experiential learning.

The remaining sections of this paper are organized as follows: The Related Work section discusses prior research and the context of this study. The Methodology section details the study design, including the setup and execution of the user study, as well as information about participants, variables, and data collection methods. The Results section presents the findings of the user study, highlighting both quantitative and qualitative outcomes. The Conclusion and Future Work section summarizes the contributions of this study, discusses its implications, and outlines directions for future research.

Related Work

Virtual reality (VR) has become a widely used tool in education with its immersive environments that enhance engagement and learning outcomes. Its applications span various fields, including STEM education, engineering, and chemical research, allowing students to practice complex procedures and explore abstract concepts in a simulated, risk-free environment. The evolution of VR from experimental head-mounted displays in the 1960s to affordable consumer-grade hardware in the 2010s has made it increasingly accessible for educational purposes [3]. The COVID-19 pandemic further accelerated VR adoption in education by providing an effective alternative to in-person learning, particularly in STEM fields, where hands-on activities are integral [21].

AN example of VR immersive environments for education is VRMC, a multisensory classroom for organic chemistry, which uses haptic gloves to teach molecular bonding, in which students can build and manipulate molecules. A study involving 13 participants demonstrated improved student motivation and understanding through this interactive approach [8]. Similarly, immersive physics laboratories have been developed to teach concepts like electric fields and Van de Graaff generators, where room-scale VR provides deeper engagement compared to mobile VR setups [14]. The 6E learning model (Engage, Explore, Explain, Engineer, Enrich and Evaluate) was applied in a VR study where students constructed a quadcopter through project-based tasks, demonstrating significant improvements in learning outcomes and practical skills [9].

In mining engineering, MiReBooks VR enables multi-user simulations, allowing students to collaboratively explore mining scenarios while guided by a teacher. This system facilitates learning in a virtual environment where students can interact with real-world mining concepts. However, performance issues such as increased latency at higher user loads highlight the challenges of scaling such systems [13]. Another notable application is MINING-VIRTUAL, which focuses on occupational safety training for miners. By immersing users in hazardous scenarios, such as equipment failures and gas leaks, it enables trainees to practice safety protocols in a controlled environment. A study with 30 participants showed high usability ratings and effectiveness in training miners [11]. Chemical engineering education has also benefited from VR applications, such as virtual labs for infrared spectroscopy. These labs replicate traditional experiments in a fully immersive setting, providing students with flexible and safe alternatives to physical labs. A study at North Carolina State University found that these virtual labs offered comparable or superior learning outcomes to traditional methods [7]. Additionally, Second Life, a virtual platform, was used to conduct typical chemistry lab tasks like titration and gas collection, achieving similar learning outcomes as physical labs while offering advantages such as easy resets and reduced distractions [20].

Architecture and construction education have adopted VR to help students explore detailed models and understand complex processes. For instance, BC/VR enables students to visualize various building phases and systems in an interactive environment. A study at Jordan University of Science and Technology found that this tool improved students' understanding of construction concepts and made learning more enjoyable compared to traditional methods [4]. Similarly, a game-based VR platform developed at Monash University simulates building utility inspections, improving students' practical knowledge of mechanical and electrical systems, though it required more time to complete compared to paper-based training [5].

Specialized fields like earthquake and marine engineering have also integrated VR for educational purposes. The SISMI-LAB project, a virtual earthquake engineering lab, allows students to modify system parameters and simulate real-world scenarios to observe dynamic responses [10]. In marine engineering, DMS-VLCC3D trains students in emergency operations such as engine room fires. This multi-user system improved students' understanding of marine engine systems and provided realistic training experiences [17].

Software engineering education has used virtual reality to make abstract computational processes more tangible. VR-ENITE visualizes sorting algorithms in 3D, helping students understand algorithms like bubble sort and insertion sort, with a 12% performance gain over traditional methods [1]. Similarly, VR-OCKS gamifies programming fundamentals for children, using interactive puzzles to teach loops and conditionals [16].

In addition, Game-based VR environments like Crazy Pot have taught mathematical concepts such as quadratic functions. A basketball simulation helped students grasp parabolic trajectories, improving math achievement and motivation [18]. In engineering education, VR systems have addressed design challenges, such as creating wheelchair-accessible kitchens, enhancing students' spatial and collaboration skills [12].

These diverse applications demonstrate the potential of VR to enhance learning in various fields. However, there is still room for improvement in how VR is used for education. While both immersive and interactive VR experiences have shown benefits, understanding the right balance of immersion and interaction is important for maximizing their effectiveness. This study aims to address this by examining how different levels of immersion and interaction impact learning, task efficiency, and engagement in the context of mining engineering education. By exploring this balance, the research seeks to provide insights into how to design better VR learning tools for complex technical subjects.

Methodology

Study Design

The primary independent variable in this study is the level of immersion and interaction within the virtual reality (VR) environment. We have designed two different VR modalities to explore how these different levels influence learning outcomes. The first modality, has less interaction and is called the passive VR modality in this study. This setup is designed to simulate traditional educational methods where users passively absorb information and observe froth flotation concepts presented through text and visuals. (Figure 1).

In contrast, the interactive VR modality provides a more immersive and engaging experience. Participants can manipulate the mineral levels and interact with the environment. In this version, interactive feedback is embedded into the environment to guide participants, making the learning process dynamic and responsive to user actions (Figure 2).

Research Questions and Metrics

The primary research question in this study is:

- Will more immersion and interaction within the VR environment lead to improved learning in an educational context?

To explore this question, we have formulated both quantitative and qualitative research questions.

Quantitatively, we aim to investigate:

- How does the level of VR interaction (passive vs. interactive) affect participants' scores on the in-game assessment of froth flotation concepts?
- Does the interactive VR modality result in faster task completion times compared to the passive VR modality?

Qualitatively, we aim to understand:

- How do participants perceive their engagement in the interactive VR modality compared to the passive VR modality?
- What challenges do participants face when navigating or interacting with the VR environments in both modalities?

The study evaluates three primary dependent variables to assess the impact of the VR modalities on learning outcomes:

1. Assessment Scores: This variable measures participants' understanding of the froth flotation process, based on their percentage of correct answers in the in-game assessment.
2. Task Completion Time: The time taken to complete the VR activity will be automatically recorded, indicating efficiency in task completion.

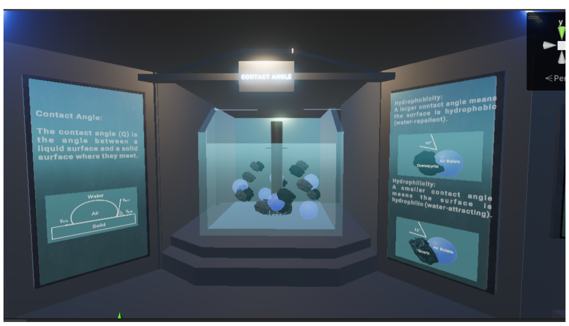

Figure 1. Passive Modality: Less interactive

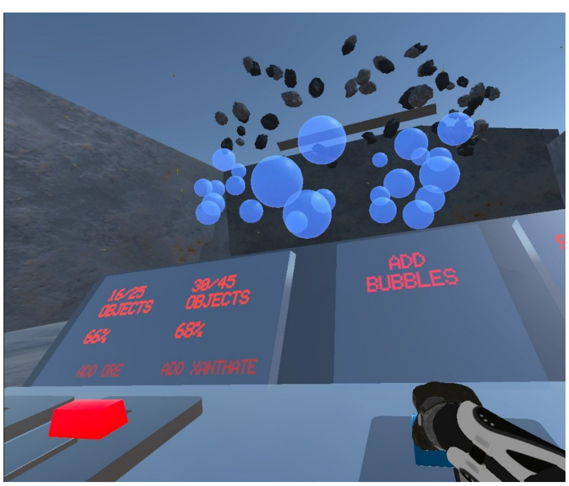

Figure 2. Interactive Modality: More interactive and Immersive

3. Engagement Levels: Engagement is measured through a post-study questionnaire, where participants rate their involvement and satisfaction with the VR environment on a Likert scale from 1 to 5.

Experimental Procedure

The study involved 12 undergraduate and graduate computer science students from the University of Nevada, Reno, with no prior VR experience or familiarity with froth flotation. This ensured results were driven by the VR modality rather than preexisting knowledge.

Participants were introduced to the VR system and completed a brief tutorial to familiarize themselves with navigation and interaction. Each participant was randomly assigned to one of two VR modalities (Figure 3), followed by an in-game assessment evaluating their understanding of the material. A post-study questionnaire was administered to gather feedback on engagement, ease of use, and perceived learning.

Figure 3. User Study in Progress

Participants completed two main tasks during the study:

1. Learning Phase:
   In the passive VR modality, participants navigate through a museum-like environment, observing different froth flotation tanks. Each tank demonstrates a specific stage of the froth flotation process, and participants learn by reading the accompanying text and viewing the visuals on information boards. In the interactive VR modality, participants start inside a froth flotation tank, where they can manipulate the mineral levels and observe the effects of their actions.
2. Assessment Phase:
   After the learning phase, participants proceed to an assessment environment which consists of 6 questions related to the froth flotation process taught during the learning phase. In this phase, they need to identify the correct objects and place them in the mini tank. The scores are recorded to evaluate knowledge retention and understanding.

VR Environment Design

The design of the VR system for this study was developed as part of the second module of the Eureka project in collaboration with the mining department at the University of Nevada, Reno. The mining department provided content specific to the froth flotation process, which includes concepts such as collector dosage, hydrophobicity and hydrophilicity, contact angle, rotation speed, and air flow, among other factors. This content was then transformed into an educational VR application, with two different modalities, passive and interactive, designed to compare different levels of immersion and engagement in the learning process.

The interactive VR modality was developed first, following the initial requirements from the mining department. In this version, participants interact with various elements of the froth flotation process by manipulating controls such as sliders that adjust mineral levels. To enhance this modality and support active learning, additional information in the form of short text and voice messages was integrated. These messages provide participants with real-time feedback, explaining how their actions, such as adding chalcopyrite, affect the overall process. The goal was to create a responsive environment that not only educates participants through exploration but also guides them by explaining the consequences of their interactions.

The passive VR modality, on the other hand, was initially designed as a museum-like experience, where users navigate through various froth flotation tanks displayed with text and visuals. Originally, this passive modality served as an introductory part of a two-stage process where users would first explore the museum environment and then transition to the interactive module for hands-on learning. However, for the purposes of this study, we modified the passive modality to function independently, ensuring that it provides a complete educational experience on its own. In the revised version, the passive environment contains all the necessary information and explanations that users need to understand the froth flotation process, without requiring engagement with the interactive module. This ensures that both modalities can stand alone as separate educational experiences.

Both VR environments were designed using Unity and tested to ensure they would work seamlessly with the Meta Quest Pro headsets and controllers. The design aimed to create immersive and intuitive experiences that would maximize learning outcomes, whether participants were passively observing or actively engaging with the content.

Results

Collected Metrics and Key Findings

The data collected during the user study is summarized in Table 1, which presents the mean values and standard deviations for all metrics across the two VR modalities: Interactive and Passive. These metrics include performance outcomes (Assessment Scores, Completion Time), user experience ratings (Engagement, Immersion), and difficulty ratings (Content Difficulty, Navigation Difficulty).

To compare the performance and experience of participants in the Passive and Interactive VR modalities, the mean values of key metrics most relevant to this study's objective (Assessment Scores, Completion Time, Engagement, and Immersion) are presented in the bar chart below (Figure 4). This visualization highlights:

1. The slightly higher Assessment Scores for the Interactive group.
2. A significant reduction in Completion Time for the Interactive group.
3. Comparable Engagement and Immersion ratings between the two groups.

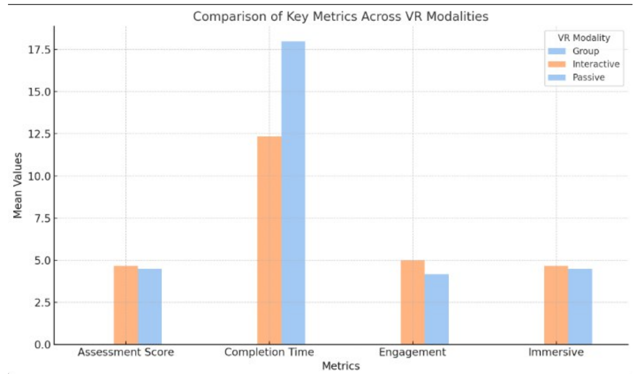

Figure 4. *Bar chart comparing the mean values of key metrics across Passive and Interactive VR modalities.*

Quantitative Analysis

- **Assessment Scores:** The average Assessment Score for the Passive group was 4.50 (SD = 1.05), while the Interactive group scored 4.67 (SD = 0.82). ANOVA revealed no statistically significant difference (F=0.09, p=0.765) indicating that both modalities were similarly effective in conveying knowledge (Table 2).
- **Completion Time:** Participants in the Interactive group completed tasks significantly faster (M=12.33, SD=3.27) compared to the Passive group (M=18.00, SD=4.69). ANOVA confirmed this difference as statistically significant (F=5.90, p=0.036) (Table 2).
- **Engagement:** Engagement scores were slightly higher in the Interactive group (M=5.00, SD=0.00) than in the Passive group (M=4.17, SD=1.33), though the difference was not statistically significant. ANOVA results supported this (F=2.36, p=0.156) (Table 2).
- **Immersion:** Immersion ratings showed no significant difference between groups. The Interactive group scored M=4.67, SD=0.52, and the Passive group scored M=4.50, SD=0.55. ANOVA indicated no significant effect (F=0.29, p=0.599) (Table 2).

Qualitative Feedback

Participants highlighted challenges such as navigation difficulties and interaction complexity in both modalities. Passive participants noted a lack of engagement compared to traditional methods. Common comments included the potential of VR to enhance learning through active engagement but also the need for improved usability.

Correlation Analysis

To track relationships between the key metrics (Assessment Scores, Completion Time, Engagement, and Immersion), a correlation matrix was calculated and visualized using a heatmap (Figure 5).

Key Findings:

Summary of Collected Metrics Across VR Modalities

Metric	Modality	Mean Value	Standard Deviation
Assessment Score	Interactive	4.67	0.82
Completion Time	Interactive	12.33	3.27
Content Difficulty	Interactive	4.00	1.10
Engagement	Interactive	5.00	0.00
Immersive	Interactive	4.67	0.52
Navigation Difficulty	Interactive	4.00	0.63
Assessment Score	Passive	4.50	1.05
Completion Time	Passive	18.00	4.69
Content Difficulty	Passive	3.17	1.33
Engagement	Passive	4.17	1.33
Immersive	Passive	4.50	0.55
Navigation Difficulty	Passive	3.83	0.98

ANOVA Results for Key Metrics

Metric	F-Statistic	p-Value
Assessment Score	0.09	0.765
Completion Time	5.90	0.036
Engagement	2.36	0.156
Immersive	0.29	0.599
Content Difficulty	1.40	0.263
Navigation Difficulty	0.12	0.734

1. **Engagement and Immersion:** The strongest positive correlation (r=0.52) indicates that participants who reported higher engagement also found the experience more immersive.
2. **Assessment Scores and Completion Time:** A weak negative correlation (r=-0.15) suggests that faster task completion might be slightly associated with better scores, though the relationship is minimal.
3. **Assessment Scores with Engagement and Immersion:** Negligible correlations (r=-0.01 and r=-0.02, respectively) indicate little direct relationship between participants' learning outcomes and their subjective experience of engagement and immersion.

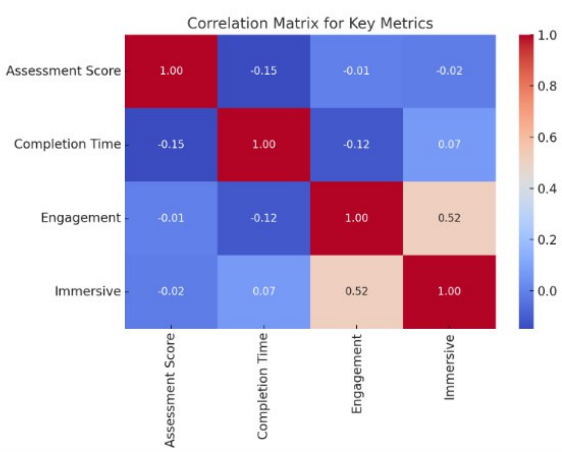

Figure 5. Heatmap of the correlation matrix for key metrics across Passive and Interactive VR modalities.

This study explored whether increased immersion and interaction in VR environments improve learning outcomes through three hypotheses. First, it was hypothesized that the interactive modality would result in higher assessment scores compared to the passive modality; however, the results showed no statistically significant difference in assessment scores (p = 0.765). Second, the interactive modality was expected to improve task efficiency, which was supported by significantly faster completion times (p = 0.036). Lastly, while it was hypothesized that the interactive modality would yield higher engagement and immersion ratings, the results showed no significant differences, though trends favored the interactive group. Qualitative feedback highlighted usability challenges with navigation and VR-specific interactions across both modalities, while participants in the interactive modality expressed greater immersion and engagement overall.

Conclusion

This study investigated how varying levels of immersion and interaction in VR environments influence learning outcomes, focusing on mining engineering education. While the quantitative findings showed no significant differences in assessment scores or engagement ratings between passive and interactive modalities, the qualitative feedback provided deeper insights. Participants expressed a preference for the interactive modality, noting that hands-on interaction made learning more intuitive, enjoyable, and less mentally taxing. These observations suggest that interactive elements may improve user experience and learning efficiency, even if it's not always evident in assessment metrics.

The improved task efficiency observed in the interactive modality highlights its potential to support active learning by reducing cognitive load and streamlining complex tasks. However, the challenges participants faced with navigation and VR-specific interactions underscore the importance of designing intuitive interfaces that incorporate diverse user experiences. This study reinforces the idea that while VR's immersive potential is promising, its success depends on balancing interactivity with usability to meet educational goals effectively.

Future work should build on these findings by addressing the study's limitations, including the small participant pool and limited scope of content covered. Expanding the sample size and incorporating a broader range of content would allow for a more comprehensive evaluation of long-term learning outcomes. Additionally, integrating multimodal feedback, such as audio, text, and real-time guidance, could enhance accessibility and engagement.

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