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Effects of Tactile Feedback on Conceptual Understanding of Electromagnetism in a Virtual Reality Experience

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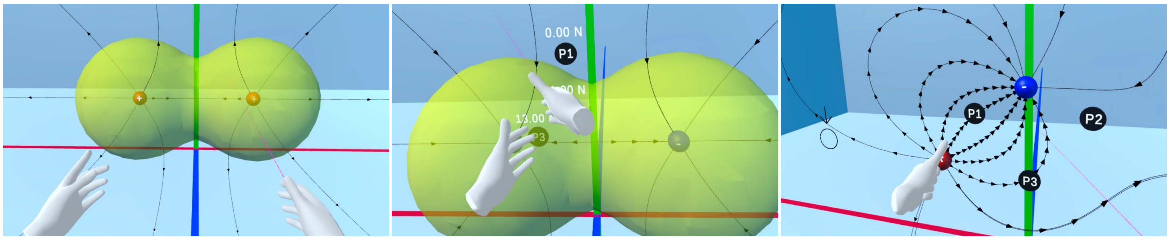

Figure 1: Students' interaction inside the virtual reality (VR) environment. Left: The initial scene. Middle: The VR hands interact with the interest points. Right: The VR hands grab and move particles in the indicated positions.

ABSTRACT

This research project aimed to investigate the effect of a virtual reality (VR) environment and tactile feedback on students' conceptual understanding of electromagnetism. In our developed application, we simulated the physics concept of electromagnetism through charged particles and their interaction through field lines and isosurfaces in 3D. We divided interactions with virtual particles into four scenarios: 1) interaction between two positively charged particles; 2) interaction between two negatively charged particles; 3) interaction between one positively and one negatively charged particle; and 4) interaction among three particles, one positively and two negatively charged. We conducted a between-group study in which undergraduate students ($n = 41$) experienced either only visual feedback ($n = 20$) or simultaneous visual and haptic feedback ($n = 21$). We found significant differences (p-value $< .05$) regarding knowledge gain in both the pretest and posttest. However, we did not find significant differences in the posttest between conditions, but the group assigned the simultaneous feedback condition indicated that tactile feedback helped them understand the electric fields. In this paper, we discuss our results' implications in designing a VR learning environment.

Index Terms: Human-centered computing—Human computer interaction (HCI)—HCI design and evaluation methods—User studies; Education—Computer graphics—Graphics systems and interfaces—Virtual reality

1 INTRODUCTION

Teaching and learning STEM-related concepts is challenging because of their abstract, counterintuitive, and cognitively demanding nature [4,7,20]. Providing simplified explanations of a scientific phenomenon is a common way of teaching STEM-related concepts [10]. However, simplifications can offer an incomplete panorama of the interactions and relationships between elements of a scientific concept (e.g., using 2D diagrams that trace the beginning and end of a phenomenon). To create significant learning experiences, instructors tend to innovate in the classroom by using new teaching strategies (e.g., cooperative, problem-based, and technology-assisted learning) [7,21,22,29].

Another way of innovating in the classroom is by implementing new technologies, e.g., using virtual reality (VR) environments for learning. VR enables learners to experience immersive environments that promote reflection and comprehension of scientific concepts [9,12,16]. Studies using VR to teach STEM-related concepts reported positive learning outcomes [12]. Also, VR enhances active engagement in learning through tactile feedback [13,30]. Embodied learning is a framework used to examine VR learning environments' value. According to the embodied learning theory, such a concept promotes the use of bodily movements as a way to acquire knowledge [1]. Moreover, physical interactions and content are well-mapped in embodied learning activities [14], in that with every movement, the learner makes an effort to learn a specific concept.

Electromagnetism is a STEM-related concept that is studied widely in discipline-based education research [8,27]. Extant studies have reported that students face problems understanding electromagnetism concepts even after receiving instruction [24]. One of the approaches examined for innovation in the classroom is using physical and virtual manipulatives (e.g., Magana et al. [18]). The theoretical framework used in the paper is "embodied learning." Embodied learning states that the body, environment, and brain regulate learning [1,5]. Thus, the brain is not a unique organ in regulating cognitive processes, e.g., problem-solving, as the body and context are problem-solving resources as well [28]. Embodied learning activities' design process comprises three elements: type of activity; materials; and facilitation [1]. With embodied learning, activities require using a human's perceptual and motor systems. The materials for embodied learning activities must be orchestrated, with feedback and actions synchronized to enhance the learning experience. All actions are goal-directed. Embodied learning environments must promote connections between actions and learning content. One

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way proposed by Abrahamson and Lindgren [1] is to ask learners to describe the feedback received (e.g., visual) and ask what the meaning is in the domain context.

This paper helps develop new learning experiences for teaching and learning electromagnetism through embodiment. Specifically, we developed a VR experience to visualize and represent electromagnetism concepts. Our study leverages advanced immersive learning experiences that promote learning in electromagnetism education. Based on our implementation, this research-to-practice study aims to answer the following research questions:

- **RQ1:** What is a VR environment's effect in promoting the conceptual understanding of complex STEM concepts, e.g., electromagnetism?
- **RQ2:** Does haptic feedback provide a learning advantage for students in understanding variations in force with respect to distance compared with visual-only feedback?

To explore these questions, we conducted a between-group study in which undergraduate students ($n = 41$) experienced either only visual feedback ($n = 20$) or simultaneous visual and haptic feedback ($n = 21$). The results indicate that users perform significantly better during the posttest, though we did not find significant differences in the posttest between conditions. However, the group assigned the simultaneous feedback condition indicated that tactile feedback helped them understand the electric fields.

This paper is divided as follows: In Section 2, we examine related literature. In Section 3, we describe the methodology used in this study with the delimited framework, materials, and design of the VR experience. In Section 4, we present the results and discuss our findings, along with conclusions and suggested directions for further research.

2 RELATED WORK

In recent years, VR technology has become increasingly popular, partially because such technology has become less expensive. Previous studies have found that VR interactions provided haptic feedback and increased cognition, user performance, and experience [2]. VR offers clear benefits, e.g., ease of controlling repetition, increased motivation, and overall advantages in terms of safety, time, space, equipment, cost efficiency, and ease of documentation [23].

In VR, a controller or gestures typically are used to interact with the virtual object. This characteristic could be beneficial in learning content design, as presented in a study by Johnson-Glenberg et al. [15] in which a mixed reality experience was developed. The authors, focusing on physics concepts concerning electric fields, conducted a study with four conditions based on the embodiment level presented with the assessment. These conditions were defined using: (1) a text-based test and keyboard; (2) a more embodied transfer test using the Wacom large tablet, including gestures to describe vectors; (3) high embodied, in which students, using a Kinect device to recognize their movements, interact with the simulated environment to grab particles, draw lines, and perform other actions; and, (4) high embodied/active with narrative. The study's findings imply that using tools that allow gestures could assess learning accurately.

In education, VR implementation provides advantages for students by using immersion as a medium for education [19]. These advantages were validated in previous studies, e.g., Shu and Huang [25], in which a VR application was developed to promote Makerspace learning. Makerspace is an open community venue that allows people of different age groups to use digital and physical technologies to explore ideas and learn manufacturing techniques and skills. These findings suggest that the VR environment allowed students to improve their Makerspace self-efficacy, capturing and keeping their attention during the delimited sessions (18-week program) more effectively than usual PowerPoint presentations (control group).

Other educational VR characteristics were examined—e.g., presence, immersion, and self-directed learning [3,26]. In Borst et al. [3], the authors presented Kvasir-VR, a framework to teach solar energy concepts to high school students in science and engineering programs. A virtual instructor approach was used to guide students during a virtual field trip. The authors compared two approaches: the in-person network and a prerecorded teacher. The teacher interface comprised 3D mapping depth camera imagery of the instructor (in the lived section) or a prerecorded view of the lessons. The teachers communicated with the students through voice commands (lived section), and the students were given instructions over the non-networked version. On the student side, raycasting and teleport motion were employed during environmental interaction (responding to questions, activating animation) and movement. In the recorded version, students were asked to respond to questions about the field trip, which provides feedback over wrong responses. The results suggest that both approaches were viewed positively, but that the live networked VR outpaced the non-networked, stand-alone version in terms of learning gains. The stand-alone version of the VR instruction contributed to an independent way of learning in which students do not require the instructor's presence during practice sessions.

Furthermore, in Simeone et al. [26], the authors conducted a study on the presence or absence of an instructor during a VR educational session. They developed two modes related to the same educational content, guided by steps and slides in the 3D environment. The first scenario allows two people to connect simultaneously, in which one assumes the role of "instructor." The instructor must guide students around the learning steps through visual indications and a commanding voice. The second mode provides students with the same content, but only with visual instructions and no one else present. The results suggest that participants immersed in the two-user version displayed a higher propensity for engaging with the interactive prompts and tasks, allowing student users to experiment with the explained concepts.

The spatial exploration of the 3D environment is viewed as the main learning outcome in studies, e.g., in Markowitz et al. [19], in which the authors focused on the use of immersive VR to learn about the effects of seawater acidity. Multiple ways to explore the environment were implemented to analyze how the students (high school and college undergraduates) performed concerning concepts that the immersive experience promoted. Therefore, participants who explored more of the virtual space formed deeper cognitive associations with the science content and could learn and recall/retain the causes and effects of ocean acidification better than those who did not explore the underwater world as much. Holly et al. [11] made other contributions on the use of a VR environment during a five-year study on teaching physics. The reflections resulted from the authors' work on the platform, in which they presented recommendations related to immersion, costs, time restrictions, and the learning process to overcome current challenges with learning and teaching using VR in the physics domain. Also, non-VR approaches were used to teach electromagnetism topics and physics concepts [6]. In Magana et al.'s [17] study, a software simulation was developed to represent the electromagnetism concept. The proposed software provided a visuo-haptic representation of the phenomenon using a Novint Falcon device, which provides a touch controller that functions like a joystick and manipulates objects on the screen. As the main contribution, the authors provided a framework for an exploratory study to validate visuo-haptic simulations. However, the low number of participants restricted the results' generalizability.

VR technology's advantages—e.g., gestures, spatial exploration, and embodiment—provide us with alternatives to promote understanding of complex STEM topics. In this study, a stand-alone VR experience was implemented, in which users observed the virtual environment through a head-mounted display (HMD). Their interactions were simulated to provide a visualization of the elec-

(a) (b)

Figure 2: A lab was used for the study. In the experiment, Oculus Quest VR headsets and other devices (a) were used by participants (b) during the study.

tromagnetism phenomenon. In the 3D environment, the user can interact with particle configurations through virtual hands. The student can observe the force's value, incidents' field lines, and isosurface generated by the particle charges as a visual cue. As for the tactile feedback, the VR controller vibrates based on the field intensity. Adding the sense of touch can increase the efficacy of computer simulations for educational purposes.

3 METHODS

3.1 Overview and Procedure

We aimed to validate VR's potential in education and compare two design approaches using a between-group study method. The main independent variable was the use of haptic feedback in the VR experience (Inclusion vs. No inclusion). Two experimental conditions were employed: only visual cues (Condition 1) and visual cues that included haptic feedback on the controllers (Condition 2). The experiment was conducted in a lab comprising 10 stations with corresponding VR headsets (Figure 2a). Each participant was assigned a station (Figure 2b). During the sessions, all participants who worked individually were not involved in any group activity during this study.

The participants were provided with a consent form that our university's IRB approved before the study began. Participants then were assigned randomly to one of the two conditions. Before any VR interactions occurred, the participants provided demographic information about their previous experience with the electromagnetism concept and their confidence in their knowledge of that topic. They answered the pretest questionnaire on paper, then the VR equipment (Oculus Quest 1) was presented to them. The participants were seated wearing a head-mounted display to interact with the 3D environment. During the VR session, the participants also were asked to answer another questionnaire on paper, requiring that they remove their headsets intermittently to write down their answers. Immediately after the VR experiment, participants took the posttest and were asked about their feelings concerning the previously experienced interaction.

3.2 Questionnaire Structure

The concepts related to electromagnetism—e.g., forces, field lines, and particles—were assessed in the surveys. We created a pretest questionnaire (Supplementary Material A) in which some demographic questions were asked about age and previous physics course experience. A drawing section also was included, in which the students were asked to draw the main interactions between particles, as shown in Figure 3. This was used to determine whether the students clearly understood how field lines describe the electric fields behavior. Four sections of questions were presented continuously. Each section was related to the scene that the student explored in the VR interface: 1) two positively charged particles; 2) two negatively charged particles; 3) one positively and one negatively charged particle; and 4) three particles, one positively and two negatively charged. These sections' questions were closely related, in which the students were asked to draw the field lines and compare and rank the points placed near the particles' influence, then select options. The final section compared two scenarios concerning particle interaction and the forces' influences over specified points.

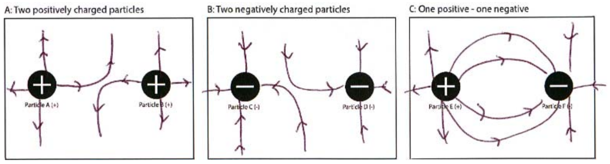


Figure 3: A Part 1 response from a student, who drew field lines in different particle scenarios.

Furthermore, a questionnaire was administered to the students during the VR experience (Supplementary Material B), comprising questions related to the experience: The students were asked how they perceived the field lines and the effect of the forces that they saw/felt at various interest points in the 3D environment. Finally, the posttest questionnaire (Supplementary Material C) was delimited with the same structure and questions as the pretest and included questions related to usability, students' perceptions about the haptic feedback, and their understanding of the electromagnetism concept during the VR experience.

3.3 The VR Interactive Interface

We developed a VR experience in the Unity game engine (2021.1.25f1) that integrates haptic feedback (`https://github.com/PedroAcevedo/electromagnetism-app`) using C# as a coding language. The VR interaction used for the experiment was implemented in Unity using the Oculus SDK. The particles were represented as 3D spheres of different colors based on the charge (red color: positive, blue color: negative), with a label indicating the sign of the charge (+ or -). Based on the delimited conditions, the particles' interaction was represented through field lines (six lines per particle) and the electric isosurfaces (we implemented the marching cubes algorithm to describe the shape). Q_1, Q_2, and Q_3 were placed over the x-axis and were movable only around the x and y positions (e.g., Figure 1 [right]). We limited each particle's movement to only two axes because the interest points were presented over a plane so that the user could perceive the distance and the tactile difference over these points. The electromagnetism concept was simulated in the VR experience, in which the students interacted in the 3D environment with the charged particles (Figure 1 [left]).

As a setting, the charges were presented on a fixed charge of 1 μC. During the experiment, the user could explore multiple scenarios with different configurations. The generated force indicated attraction in the scenarios with chosen values and different signs ($Q_1 + Q_2-$ or $Q_1 - Q_2 + Q_3-$). The repulsive force was generated in the scenes with chosen values and equal signs ($Q_1 + Q_2+$ or $Q_1 - Q_2-$). Coulomb's law describes the actual force:

$$\vec{F} = K \frac{Q_1 Q_2}{R_{QQ}^2} \hat{r} \tag{1}$$

where $K = 8.987x10^9 \frac{Nm^2}{C^2}$ is the Coulomb's constant, $\hat{r}$ is the unit vector, and

$$R_{QQ} = dist|Q_1, Q_2| \tag{2}$$

is the Euclidean distance between the locations of charges Q_1 and Q_2. Equations 1 and 2 were implemented to simulate the electromagnetism phenomenon, e.g., field lines and force values. We used the Line Renderer component to draw the field lines. Every line, incoming and outgoing, was drawn according to the particle's behavior, including the corresponding direction (positive pointing out and negative pointing in). The lines were displayed based on the incident force over the 3D coordinates. By particle, lines were drawn on a coordinate according to the force's direction until they reached a particle or went outside the limit. Furthermore, for the particle's interaction, we used the collider component that the engine provided. This collider allows for recognizing the sphere's shape to provide the object interaction during the user grab action. When a user grabs a particle, the scenario resets the simulation values around the particle's new position. The field lines, isosurfaces, and forces then are recalculated. The field lines are calculated every frame, so all lines are updated even if the particles' positions change. Notably, the isosurface and forces, calculated when the particles were stationary again, occurred when the users released the node from the virtual hand.

The simulation included guidelines and visual cues that the participants followed to interact with the designed environment. Points close to the particles are called Interest points. When the user interacts with those points the coordinate's force value is displayed on the 3D scene (viewed as a visual clue, as stated in Section 3.1). The user could see the force value only if they put one of the virtual hands near the interest point (Figure 1 [middle]). Finally, we include instruction on an user interface (UI) to guide the user on the experiment (Figure 4a). The user employed the raycasting mechanism to interact with the UI in the environment (Figure 4b). In the introduction scene, the user could select his preferred hand to use the ray during the session. The incident forces were mapped to the controllers' vibration intensity to provide tactile feedback. Through a min-max normalization, the incident force in each 3D coordinate was mapped to the vibration interval between 0 and 1, so that when the users moved around the virtual hand, they could feel the electric fields' effect in these areas.

4 RESULTS AND DISCUSSION

4.1 Participant Demographic Data

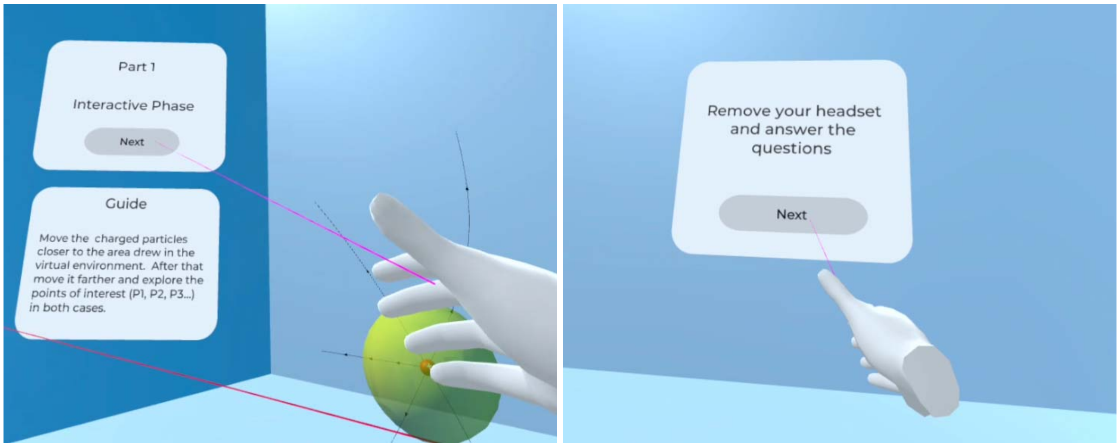
To recruit participants, we emailed undergraduate students in a technology program at a Midwest university during Spring 2022. Altogether, 41 students (20 for Condition 1 and 21 for Condition 2) volunteered to participate (age: $M = 18.98$, $SD = 1.19$). Out of this sample, 31 participants were male, and 10 were female. Moreover, 31 participants were first-year students, eight were second-year students, and two were third-year students with an engineering emphasis. Also, only 11 participants did not take any physics-related college courses. Finally, when the participants stated whether they ever had used VR before, 36 answered yes, and only five answered no.

4.2 Study Conditions Analysis

Both groups responded to the pretest questionnaire, with no significant differences ($p > .05$) found in the results. Before testing for validity, we conducted a paired t-test by condition to verify whether participants had different results during the pretest and posttest questionnaires. For Condition 1, with a p-value lower than the significance level ($p = .036$), enough evidence was found to affirm a significant difference between the pretest and posttest results. The students performed better on the posttest, ($M = 53.64$ [14.31]) than the pretest ($M = 47.18$ [18.02]). Conversely, for Condition 2, we found a significant difference between the pretest and posttest results based on p-value ($p = .017$). Also, the posttest results reflected better comprehension of the concept ($M = 54.91$ [11.53]) than the pretest results ($M = 47.19$ [13.35]). Furthermore, from the Cohen's d value, we found a medium effect on the means for Conditions 1 and 2, with values of .571 and .504, respectively. In response to **RQ1**, the previous results suggested that the VR environment exerted a positive effect on the conceptual understanding of the topic, indicating that the use of the developed VR experience was effective in teaching students. The experimentation component allowed the students to explore the concept of electromagnetism in an immersive and interactive environment, which also instructed them on how to draw electric lines on their responses. In the initial pretest, some students (10%) used isolines to represent the particles' interactions; however, none of the participants used the isolines in their posttest responses.

Considering the inferential test's gain value (see Figure 5), we found no significant difference in the conditions' results. The VR experience's effect remains equal with or without the tactile feedback component. As for **RQ2**, inclusion of haptic feedback did not provide an advantage compared with the visual-only condition. Even though the results from the students' perceptions (Figure 6), specifically their responses to the statement "The tactile feedback provided by the controls helped me understand electric fields" (Feedback 1) and considering only the participants in Condition 2, we found that more than 50% percent of the participants (71.5%) stated that they "Agree" or "Strongly Agree" with this statement, i.e., they perceived the inclusion of haptic feedback positively. When considering the statement "The tactile feedback was easy for me to interpret" (Feedback 2), students mostly chose "Strongly Agree," i.e., the tactile feedback's learning objective was reached. The students interpreted the use of tactile feedback in their representations of the electric fields' phenomenon.

As for the included visual cues, the participants were asked about the visual component in the virtual environment to understand the electromagnetism concept. When asked to consider the statement *"The visual information provided by the simulation helped me understand electric fields"* (Visual 1), most participants (92.7%) stated that the visual information helped them comprehend the electric fields concepts. When considering the statement *"The visual information was easy for me to interpret."* (Visual 2), 41.5% responded "Strongly Agree" and 51.2% "Agree."



Part 1

Interactive Phase

Guide

Move the charged particles closer to the area drew in the virtual environment. After that move it farther and explore the points of interest (P1, P2, P3...) in both cases.

Remove your headset and answer the questions

(a)

(b)

Figure 4: The user interfaces on the 3D environment: (a) guidelines during the experience and (b) instruction to remove the headset to respond questionnaire on paper.

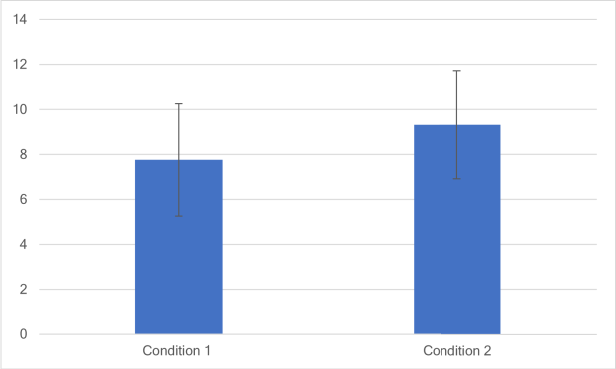


Figure 5: Gain error bar chart for the two conditions of our study.

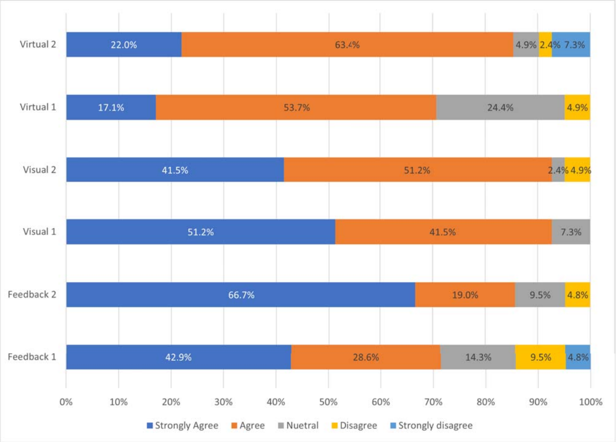


Figure 6: Students' perception results.

Finally, considering the VR principles, the participants were asked about the experimentation component and the VR experience. As for the statement *"The visual information was easy for me to interpret."* (Virtual 1), 70.8% responded positively ("Agree" or "Strongly Agree"), while only 4.9% chose "Disagree." However, when responding to the statement *"I remember how to use the virtual simulation from the previous activity"* (Virtual 2), 63.4% and 22% responded "Strongly Agree" and "Agree," respectively. These results indicated that the use of VR in the experiment was accurate based on the user's perspective.

5 CONCLUSION

We examined the implementation and use of a virtual environment to teach complex physics concepts, e.g., electromagnetism. The implemented VR experience comprised four scenarios that simulated the phenomenon through charged particles and their interaction through field lines and the isosurface in 3D. We also enabled haptic feedback by implementing controllers' vibrations, i.e., participants were able to move particles around the 3D environment to visualize field lines' behavior.

A between-group study was conducted to assess the users' perceptions and adoption of the VR technology for learning purposes. Undergraduate technology students at a Midwest university during Spring 2022 participated in the study. Two conditions were delimited: Only visual cues and visual cues with tactile feedback on the controllers. Our results suggest that using VR and the implemented 3D simulation may facilitate conceptual comprehension of electric fields. The posttest's results were better in both conditions, with a medium effect on the mean difference, even though we did not find significant differences in the posttest between conditions.

Students' perceptions of the VR experience were positive overall. They agreed about the statements on the use of VR and implementation of this experiment. They also found the visual cues included in the 3D environment to be helpful to their understanding of electromagnetism concepts. Finally, for the tactile feedback component, students from Condition 2 viewed it as easy to interpret and valuable in understanding the electric fields. Future studies should be conducted to evaluate implementation of VR on various complex STEM topics. A more extensive study with more participants could be conducted, and we also could include more concepts related to electromagnetism to provide a more general scope of VR use on this topic.

5.1 Limitations

The study contains some limitations, one of which was the length of the experiment's duration. The students may have felt overwhelmed taking an hourlong test about the electromagnetism concept. An ideal way to address in future research this might be to provide a break between the VR experience and posttest questionnaire, or maybe give students one hour or a day to complete the questionnaire to provide more motivation. Furthermore, concerning the VR and questionnaire process, the short explorations between scenes, in which the students removed their headsets intermittently to answer questions on paper, should be reviewed. Even though it was helpful to rest and avoid simulation sickness, for future studies, it would be more ideal to administer the questionnaires on the virtual environment in such a way that the students need not remove their headsets frequently (each user had to remove them four times). As for the questionnaires, the participants did not answer many questions related to drawing the electric lines. Considering that we asked participants to draw multiple times, reducing these questions in future research would be necessary. Also, we could have included more open-ended questions about the VR tool/environment in the final part to collect more extensive feedback on the user experience.

REFERENCES

[1] D. Abrahamson and R. Lindgren. Embodiment and embodied design. In R. Sawyer, ed., *Cambridge handbook of the learning sciences*, pp. 358–376. Cambridge University Press., Cambridge, second edi ed., 2014.

[2] C. Basdogan, C.-H. Ho, M. A. Srinivasan, and M. Slater. An Experimental Study on the Role of Touch in Shared Virtual Environments. *ACM Trans. Comput.-Hum. Interact.*, 7(4):443–460, dec 2000. doi: 10.1145/365058.365082

[3] C. W. Borst, N. G. Lipari, and J. W. Woodworth. Teacher-guided educational vr: Assessment of live and prerecorded teachers guiding virtual field trips. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 467–474, 2018. doi: 10.1109/VR.2018.8448286

[4] S. B. Day, B. A. Motz, and R. L. Goldstone. The Cognitive Costs of Context: The Effects of Concreteness and Immersiveness in Instructional Examples. *Frontiers in Psychology*, 6, dec 2015. doi: 10.3389/fpsyg.2015.01876

[5] P. Dourish. *Where the action is: The foundations of embodied interaction*. MIT Press, Cambridge, 2001.

[6] B. J. Dringoli, K. Kolosova, T. J. Rademaker, J. Wray, J. Choquette, and M. Hilke. Content sequencing and its impact on student learning in electromagnetism: Theory and experiment, 2019. doi: 10.48550/ARXIV.1910.00145

[7] A. Fathurohman, E. Susiloningsih, and A. Arianti. Physics module based on {STEM} problem based learning on newton's motion law material for senior high school. *Journal of Physics: Conference Series*, 1869(1):12155, apr 2021. doi: 10.1088/1742-6596/1869/1/012155

[8] C. Furió, J. Guisasola, J. M. Almudí, and M. Ceberio. Learning the electric field concept as oriented research activity. *Science Education*, 87(5):640–662, jul 2003. doi: 10.1002/sce.10100

[9] A. Garmpis and N. Gouvatsos. Design and development of WebUbu: An innovating web-based instruction tool for Linux OS courses. *Computer Applications in Engineering Education*, 24(2):313–319, 2016. doi: 10.1002/cae.21706

[10] J. C. Hayes and D. J. M. Kraemer. Grounded understanding of abstract concepts: The case of {STEM} learning. *Cognitive Research: Principles and Implications*, 2(1), jan 2017. doi: 10.1186/s41235-016-0046-z

[11] M. Holly, J. Pirker, S. Resch, S. Brettschuh, and C. Guetl. Designing VR Experiences -Expectations for Teaching and Learning in VR. *Educational Technology & Society*, 24:107–119, 2021.

[12] Y. Jiang, V. Popov, Y. Li, P. L. Myers, O. Dalrymple, and J. A. Spencer. "it's like i'm really there": Using vr experiences for stem career development. *Journal of Science Education and Technology*, 30(6):877–888, jul 2021. doi: 10.1007/s10956-021-09926-z

[13] M. C. Johnson-Glenberg. Immersive {VR} and Education: Embodied Design Principles That Include Gesture and Hand Controls. *Frontiers in Robotics and {AI}*, 5, jul 2018. doi: 10.3389/frobt.2018.00081

[14] M. C. Johnson-Glenberg. The Necessary Nine: Design Principles for Embodied VR and Active Stem Education. pp. 83–112, 2019. doi: 10.1007/978-981-13-8265-9_5

[15] M. C. Johnson-Glenberg and C. Megowan-Romanowicz. Embodied science and mixed reality: How gesture and motion capture affect physics education. *Cognitive Research: Principles and Implications*, 2(1), may 2017. doi: 10.1186/s41235-017-0060-9

[16] R. Lindgren and M. Tscholl. Enacted misconceptions: Using embodied interactive simulations to examine emerging understandings of science concepts. Boulder, CO: International Society of the Learning Sciences, 2014.

[17] A. J. Magana and S. Balachandran. Unpacking students' conceptualizations through haptic feedback. *Journal of Computer Assisted Learning*, 33(5):513–531, jun 2017. doi: 10.1111/jcal.12198

[18] A. J. Magana, M. Serrano, and N. S. Rebello. A sequenced multimodal learning approach to support students' development of conceptual learning. *Journal of Computer Assisted Learning*, p. jcal.12356, 2019. doi: 10.1111/jcal.12356

[19] D. M. Markowitz, R. Laha, B. P. Perone, R. D. Pea, and J. N. Bailenson. Immersive virtual reality field trips facilitate learning about climate change. *Front. Psychol.*, 9:2364, Nov. 2018.

[20] M. A. Rau and T. Herder. Under which conditions are physical versus virtual representations effective? Contrasting conceptual and embodied mechanisms of learning. *Journal of Educational Psychology*, 113(8):1565–1586, nov 2021. doi: 10.1037/edu0000689

[21] A. P. Rehmat and K. Hartley. Building Engineering Awareness: Problem Based Learning Approach for {STEM} Integration. *Interdisciplinary Journal of Problem-Based Learning*, 14(1), may 2020. doi: 10.14434/ijpbl.v14i1.28636

[22] P. Rillero and Y.-C. Chen. The Use of a Digital Problem-Based Learning Module in Science Methods Courses. *Journal of Problem Based Learning in Higher Education*, p. Vol. 7 No. 1 (2019), 2019. doi: 10.5278/OJS.JPBLHE.V7I1.2349

[23] A. Rizzo, J. G. Buckwalter, C. van der Zaag, U. Neumann, M. Thiebaux, C. Chua, A. van Rooyen, L. Humphrey, and P. Larson. Virtual environment applications in clinical neuropsychology. In *Proceedings IEEE Virtual Reality 2000 (Cat. No.00CB37048)*, pp. 63–70, 2000. doi: 10.1109/VR.2000.840364

[24] U. A. Shaikh, A. J. Magana, L. Neri, D. Escobar-Castillejos, J. Noguez, and B. Benes. Undergraduate students' conceptual interpretation and perceptions of haptic-enabled learning experiences. *International Journal of Educational Technology in Higher Education*, 14(1), 2017. doi: 10.1186/s41239-017-0053-2

[25] Y. Shu and T.-C. Huang. Identifying the potential roles of virtual reality and {STEM} in Maker education. *The Journal of Educational Research*, 114(2):108–118, feb 2021. doi: 10.1080/00220671.2021.1887067

[26] A. L. Simeone, M. Speicher, A. Molnar, A. Wilde, and F. Daiber. Live: The human role in learning in immersive virtual environments. In *Symposium on Spatial User Interaction*, SUI '19. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3357251.3357590

[27] W. M. Thong and R. F. Gunstone. Some student conceptions of electromagnetic induction. *Research in Science Education*, 38(1):31–44, 2008.

[28] A. Wilson and S. Golonka. Embodied Cognition is Not What you Think it is. *Frontiers in Psychology*, 4(February):1–13, 2013. doi: 10.3389/fpsyg.2013.00058

[29] H.-Y. Yeh, Y.-H. Tsai, C.-C. Tsai, and H.-Y. Chang. Investigating Students' Conceptions of Technology-Assisted Science Learning: a Drawing Analysis. *Journal of Science Education and Technology*, 28(4):329–340, jan 2019. doi: 10.1007/s10956-019-9769-1

[30] Y. Zhou, S. Ji, T. Xu, and Z. Wang. Promoting Knowledge Construction: A Model for Using Virtual Reality Interaction to Enhance Learning. *Procedia Computer Science*, 130:239–246, 2018.