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Embodied immersive virtual reality to enhance the conceptual understanding of charged particles: A qualitative study

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ABSTRACT

Learning in science, technology, engineering, and mathematics (STEM) is often challenging due to the abstract and counterintuitive nature of some concepts. Computer-based learning has emerged as an alternative method to help improve students' comprehension of these complex topics, even though technological tools must be supported with pedagogical strategies, technology affordances, sound design, and structured activities to teach scientific concepts properly. In that sense, we propose the design of an immersive virtual reality (IVR) experience, including visual and haptic cues to facilitate learning about electric fields (EFs) and charged particles (CPs) concepts. We scaffolded our design tool based on embodied design principles and cognition. The IVR experience allows learners to manipulate the components of point charges (e.g., particles, distance between particles, and charges) to learn electricity concepts. We conducted a qualitative study ($N = 8$) to assess the designed application. The sample included undergraduate students (five male and three female) from technology-related fields with some or no prior knowledge of high school or higher education physics. We assessed study participants' conceptual understanding through a pretest-posttest and conducted a brief interview to identify their expected interaction with the designed affordances. Screen recording and the System Usability Scale (SUS) are the other metrics of interest in defining study participants' performance and experience. The collected data and thematic analysis suggested that participants recognized the included affordances based on the embodied design principles and used them to interact, link previous knowledge, and identify the different factors to explain the physics phenomenon. Additionally, we provided insights for designing IVR experiences to promote conceptual understanding of complex STEM topics based on embodied learning principles.

1. Introduction

Providing significant learning experiences in science, technology, engineering, and mathematics (STEM) can be challenging (Dass, 2015; Day, Motz, & Goldstone, 2015; Kempa, 1991). The abstract nature of some STEM-related concepts demands cognitive tasks that require suitable scaffolding to leverage students' learning (Belland, 2017; Devolder, van Braak, & Tondeur, 2012). Various techniques, frameworks, and guidelines for teaching and learning in STEM have been proposed in previous studies (Allen, Webb, & Matthews, 2016; Billiar, Hubelbank, Oliva, & Camesano, 2014; Felder & Brent, 2016; Stohlmann, Moore, & Roehrig, 2012). One way to teach STEM is through simplified explanations of scientific phenomena (Hayes & Kraemer, 2017). However, such explanations provide an incomplete understanding. In this context, computer-based learning has emerged as an alternative method in promoting students' understanding of these complex topics due to the interactive simulations of scientific concepts (Çalışkan, Selçuk, & Erol, 2010; D'Angelo et al., 2014).

One highly abstract concept in STEM is electromagnetism, which is widely studied in discipline-based physics education research (Furió, Guisasola, Almudí, & Ceberio, 2003). Studies have reported that students have difficulty understanding electromagnetism concepts even

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after instruction (Shaikh et al., 2017). The challenges in learning about electromagnetism can be explained as analogous to how early scientists tried to explain and model this phenomenon (Dori & Belcher, 2005; Pocovi & Finley, 2002). Among these difficulties, it was found that (a) students struggle to apply Newton's third law or the symmetry of Coulomb's law on charged particles (CPs) settings, (b) students have difficulty identifying how a new CP affects the direction of the force or field, and (c) students are confused about distinguishing magnetic field effects from electric field effects. These issues were reported in a large study involving 5000 undergraduate students (Maloney, O'Kuma, Hieggelke, & Heuvelen, 2001). Specifically regarding the CP concept, the conceptual understanding of its interaction leads students to comprehend and link the theory behind it to advanced topics in modern physics and engineering (Bagno & Eylon, 1997; Magana et al., 2022).

Therefore, electromagnetism a difficult and abstract concepts in science can be enhanced through computer-based learning by using simulations to visualize abstract phenomena (Dega, Kriek, & Mogese, 2013). These simulations can include features that help students understand various concepts and factors, such as immersion and the sense of touch (Neri et al., 2015). Various studies have explored these alternatives for teaching complex STEM topics such as electromagnetism. For example, Magana and Balachandran (2017) developed a simulation to represent electromagnetism by interacting with a Novint Technologies' Falcon desktop haptic device. When manipulating objects on the screen, the proposed method uses haptic feedback to provide a visuo-haptic representation of the phenomenon. The authors provided a framework for an exploratory study to validate visual-haptic simulations. The use of pedagogical alternatives such as embodied learning was explored in the study by Johnson-Glenberg and Megowan-Romanowicz (2017), which describes a mixed-reality experience. Focusing on physics concepts relating to EFs, the authors conducted a study where participants were assigned to four conditions based on the embodiment level. These conditions were: (a) a text-based test taken using a keyboard; (b) a test using a Wacom large tablet that allows gestures to create vectors; (c) interaction through a Kinect device that recognizes movements; and (d) high embodied/active with narrative. The study findings suggest the effectiveness of the high embodied condition over the traditional condition or conditions with less embodiment. The findings support the theory that using the body during the learning process can have beneficial results in terms of students' (Abrahamson & Lindgren, 2014).

Implementing immersive technologies in STEM (e.g., immersive virtual reality [IVR]) provides a more direct way to interact with the content by enhancing the visualization and interactivity of complex scientific concepts (Liu, Wang, Koszalka, & Wan, 2022). IVR can promote the reflection and comprehension of invisible concepts (Johnson-Glenberg, 2019; Lindgren & Tscholl, 2014). It offers a level of immersion that isolates the real world, minimizes distractions, and provides students a sense of presence and agency in their learning experience (Klingenberg, Fischer, Zettler, & Makransky, 2023; Makransky & Petersen, 2019). Studies using IVR to teach STEM-related concepts have reported positive learning outcomes (Jiang et al., 2021; Kavanagh, Luxton-Reilly, Wuensche, & Plimmer, 2017). Regarding IVR in education, there is a need to consider the different potentialities offered through an appropriate instructional design and the necessary affordances to improve learning (Johnson-Glenberg, 2019; Makransky & Mayer, 2022).

In this study, we propose an IVR experience to facilitate learning about electric fields (EFs) and CPs. The embodied design principles and cognition are the basis of the designed IVR experience (Abrahamson & Lindgren, 2014). Our aim is to address the learning of CP concepts through an interactive learning experience featuring the simulation of CP interactions, including Coulomb's law equations and EF visualization. This facilitates the students to explore applied forces and EF effects on different CP settings in an immersive manner. We also explore participants' perceptions of our virtual reality (VR) application. We believe the study participants would notice and use the included affordances in our designed VR experience.

2. Related work

2.1. Conceptual understanding of electromagnetism

In science-related studies, students tend to have misconceptions about concepts that might reflect improper knowledge acquisition and poor comprehension of the topics (Schultz et al., 2017). STEM education is multidisciplinary and requires innovative methods and materials. These materials facilitate a deeper understanding and critical thinking that links the participants' conceptual knowledge. Specifically, previous research has focused on investigating common students' difficulties with the conceptual understanding of physics. These difficulties are still present, even at the university level, where difficulty understanding basic concepts and misconceptions about various phenomena can persist (Georgiou & Sharma, 2021). One such phenomenon is electromagnetism, considered one of the most challenging concepts in physics (Magana & Balachandran, 2017). EFs imply connecting electricity and magnetism-related concepts, such as current, voltage, energy, and power (Maloney et al., 2001). CP interactions relate to multiple electromagnetism theories, such as Faraday's and Coulomb's laws, which describe the behavior of charges and the consequences of EFs. These concepts should be learned progressively to improve understanding of electric interactions (Furió et al., 2003). Various studies have reported study participants' difficulties in reasoning about and understanding EFs and magnetism (Viennot & Rainson, 1992; Wheatley, Wells, Henderson, & Stewart, 2021). The aforementioned suggests finding alternatives that can mitigate this problem and enhance learning for this complex STEM concept.

2.2. Learning with immersive virtual reality

Interactive technologies involving 3D environments, mixed reality, and IVR can help promote learning (Ibáñez, Serio, Villarán, & Kloos, 2014). IVR has been used as a learning alternative for training because it provides engaging experiences simulating real-world tasks (Kavanagh et al., 2017). Additionally, the cost of VR devices has decreased dramatically in recent years, allowing their extended use for education (Hickman & Akdere, 2018). Potential learning enhancement through IVR is a recently explored research topic (Radianti, Majchrzak, Fromm, & Wohlgenannt, 2020). Previous studies suggest that IVR learning experiences promote engagement, motivation, and learning outcomes in multiple science-related topics (Kuhail, ElSayary, Farooq, & Alghamdi, 2022; Pellas, Dengel, & Christopoulos, 2020). Parong and Mayer (2018) compare IVR interaction and traditional slideshow lessons for a biology topic. In their VR environment, they provide narration and immersive animations of the circulatory system and parts of cells. The results of one of their experiments showed lower learning outcomes for the VR lesson group, even though motivation, interest, and engagement ratings were higher than for the slideshow group.

Ferrell et al. (2019) provided college students a way to visualize and interact with molecular dynamics using VR. They compared VR usage with the traditional slideshow format, finding that participants were more motivated and showed higher learning gains after the VR session. However, the authors did not detail the theoretical framework or learning principles used in designing their tool. In physics education, Pirker, Lesjak, and Guetl (2017) designed the Maroon VR tool, which offers multiple interactive physical simulations. They created a room-scale laboratory with different stations for experiments on EFs. Their results suggest that this setup is well accepted for learning physics, highlighting the significant benefits of simulations and visualizations in promoting engagement through hands-on learning. However, the researchers did not provide specific details about the sample used, as it included participants with diverse backgrounds, such as students and employees, who may experience the VR scenario differently. For mathematics, Shi, Wang, and Ding (2022) proposed a game-based VR experience to teach quadratic functions. They developed a pot-shooting game where the trajectory of projectiles illustrates the underlying mathematics, specifically the parabolic graph of quadratic functions. Their results showed a significant improvement in math learning from the pretest to the posttest among K12 students who experienced the VR game.

Regarding embodied learning through IVR, Johnson-Glenberg, Bartolomea, and Kalina (2021) evaluated different degrees of embodiment and platforms (VR vs. PC) for learning biology-related concepts. They designed a "Catch a Mimic" VR game where participants used gestures, like moving a net, to catch butterflies and complete the game. They also included leaderboards, instructions, and audio feedback. Similarly, Chatain et al. (2022) followed the embodied design framework by Abrahamson & Lindgren, 2014 to propose an IVR activity for learning derivatives, incorporating gestures to move curves and represent slopes based on hand positions and movements. They conducted a study comparing different embodiment levels but found no differences in learning outcomes. These studies highlight the importance of grounding IVR learning activities in embodied designs or frameworks that could potentially enhance students' learning gains in STEM topics.

2.3. Learning with haptics

Touch is one of the essential ways to interact with our environment. Touch or haptics is a critical non-verbal communication method that scaffolds meaningful conceptual learning (Edwards, Bielawski, Prada, & Cheok, 2018; Neri et al., 2015). Haptic mapping or rendering is the process in which the user can feel, touch, and manipulate virtual objects through a haptic interface. These haptic capabilities extend simulations, promoting different levels of immersion in participants' interactions (Johnson-Glenberg & Megowan-Romanowicz, 2017). Desktop VR experiences with the addition of a haptic device (e.g., Novit Falcon) have been developed around science concepts such as friction (Yuksel et al., 2019), fluids/hydraulics concepts (Hamza-Lup & Sopin, 2009), chemical bonding (Zohar & Levy, 2021), and EFs (Hamza-Lup & Goldbach, 2020; Neri et al., 2020; Shaikh et al., 2017). Haptic devices provide forced feedback to users once they interact with the simulation, for example, by grabbing a virtual object. The findings on this topic suggest the effectiveness of haptic devices for conceptual understanding in addition to other benefits, such as the novelty of the device catching participants' attention compared to traditional laboratory experiments (Hamza-Lup & Goldbach, 2020) and possible cognitive load during their interaction due to the different types of stimuli (Shaikh et al., 2017). Edwards et al. (2018) proposed a gamified multisensory VR experience for chemistry education on basic hydrocarbon and molecule formation using haptic feedback through gloves with integrated vibration motors and sensors. The haptic gloves allow the user to "touch" the molecules via vibration feedback on each of the fingers and hands during the interaction. Acevedo et al. (2022) proposed the design of a tactile feedback experience for the conceptual understanding of electromagnetism. The haptic feedback provides a way to "feel" the intensity of the electric force exerted on particles. Haptics in IVR scenarios imply using external devices such as gloves and motor equipment to simulate force feedback with accurate fidelity and thus higher costs and difficulty accessing the technology (Sanfilippo et al., 2022). Haptic learning experiences in IVR are challenging and scarce and have not shown reliable results (Edwards et al., 2018; Lontschar, Deegan, Humer, Pietroszek, & Eckhardt, 2020). Therefore, more research is needed to determine the value of haptic feedback in VR experiences related to STEM learning.

2.4. Contributions

Previous studies have explored the use of IVR for learning by leveraging interactions and visualizations of various STEM concepts (Ferrell et al., 2019; Parong & Mayer, 2018; Pirker et al., 2017; Shi et al., 2022). However, there is a need to analyze the specific features that justify the use of immersive technologies for complex STEM topics. Additionally, many VR experiences have focused on the functionality and novelty of interactions, often neglecting students' needs and the scaffolding provided by learning theories (Radianti et al., 2020). To better understand the effectiveness of IVR in STEM, specifically for higher education, it is essential to examine implementations based on theoretical frameworks that explain how learners benefit from these affordances.

In this study, we designed an IVR application grounded in embodied learning and cognition theories to enhance the learning of CPs and EFs. Building on prior research in embodied learning design for IVR (Chatain et al., 2022; Johnson-Glenberg et al., 2021), in this study, we aimed to (a) expand knowledge on the use of IVR for training and learning and (b) provide insights into designing embodied experiences with affordances that promote conceptual understanding. We conducted a qualitative study using the designed IVR tool to explore whether participants noticed and utilized the designed affordances in the lesson and activity. Our findings could inform researchers and instructional designers about IVR's expected features and interactions and how embodied learning and cognition can scaffold IVR lessons to enhance conceptual understanding.

3. Theoretical framework

3.1. Embodied cognition

We considered embodied cognition the theoretical framework guiding the proposed design (Shapiro, 2010). The definition of embodied cognition emphasizes the role of sensory and motor functions in cognition, and therefore, embodied cognition refers to the importance of the body in the functioning of the mind. Flogia and Wilson (Foglia & Wilson, 2013) state that "The body intrinsically constrains, regulates, and shapes the nature of the mental activity." Wilson and Golonka (Wilson & Golonka, 2013) explain this theory from a psychological perspective, stating that "Embodied cognition implies that there are resources, plural, available to the organism. These resources include the brain, body, environment, and relations between these things (e.g., the motion of our bodies through the environment)."

Considerable research on learning and cognition from the perspectives of philosophy, psychology, linguistics, neuroscience, and computer science have contributed to changing views about traditional cognitivism and the mind, which excludes body-mind dualism (Shapiro, 2010). In that sense, the embodiment of learning could be considered a "circular" process that distinguishes between our actions and previous experiences that could affect learning (Maturana & Varela, 1987). Studies have been conducted to prove the implications of embodied cognition, such as in language processing. Glenberg et al. (2008) performed several experiments that reveal a surprising connection between a subject's capacity to understand a sentence and bodily actions a subject is asked to perform before or during judgments of sentence sensibility.

The relevance of gestures has been analyzed, and their importance in acquiring mathematical concepts has been suggested (Alibali & Nathan, 2012). Shapiro and Stolz (2018) summarize four learning implications of embodiment in instruction: (a) teachers should look for gestures to determine students' comprehension; (b) the use of gestures in teacher instruction encourages learners to produce or imitate gestures that can enhance learning; (c) gestures can be categorized in terms of different purposes, which can facilitate effective communication; and (d) embodiment provides a casual route to more effective learning or a means of measuring conceptual understanding.

3.2. Implications for the design of learning materials

The implications of the theoretical framework for the learning material design relate to the integration design principles proposed by

Abrahamson and Lindgren (2014). These principles suggest that embodied design leads to conceptual development when the participants strategize to interact with learning materials. The authors provide guidelines (**activities**, **materials**, and **facilitation**) for embodied design based on the theory of cognition and in response to the pedagogical challenge of expediting learning conception. The design should promote using the participants' perceptual senses and kinesthetic coordination to process stimuli and judge new action choices for the **activities**. Regarding the **materials**, the learning environment should be designed to provide feedback in response to participants' inputs or actions in a progressive way. These actions demand that the participants develop perceptuomotor schemas to control and manipulate the tools. Regarding **facilitation**, the design should include physical cues to promote body engagement and spatial connections to achieve the expected conceptual development of the participants. The participants should be able to construct strategies to interact with the material in the environment.

In this sense, the content, which describes the IVR scenarios, reflects the embodied design principles.

- **Activities:** Activating participants' kinesthetic coordination by movements required in a virtual 3D environment (see Fig. 1a). A worksheet presents the content progressively through different particle configurations.
- **Materials:** Including manipulatives and virtual objects in a simulation of the electromagnetism phenomenon (see Fig. 1c). The participants can interact with the objects, and the current configuration is transformed based on the participants' inputs.
- **Facilitation:** The phenomenon is simulated in the virtual 3D environment through the representation of visual and haptic cues. These cues are included as "functional metaphors" to reinforce the desired conceptual insights through the participants' physical interactions. Additionally, by scene, the participants follow a sequence of predict-experiment-validate by exploring and inferring about the particles' behavior or effects.

This approach is selected due to the immersive nature of IVR and the advantage that body interactions can have for participants' learning (Shapiro & Stolz, 2018). Bodily experience can enhance learning, even for abstract concepts (Holly, Pirker, Resch, Brettschuh, & Guetl, 2021). Abrahamson and Lindgren (2014) state that "Conceptual reasoning originates in physical interaction and becomes internalized as simulated actions." During an IVR experience, the participants perform actions that simulate real-life interactions, such as grabbing an object, moving their hands, or walking. These interactions or gestures are physical actions that activate the participants' sensory motor neurons, thus increasing memory trace strength (Johnson-Glenberg, 2019).

3.3. Physics Concept: Coulomb's law and electric field lines

The learning content is focused on the particle interactions and electric field lines explained from Coulomb's law and Faraday's principles. Coulomb's law quantifies the interaction between two static CPs as an electric force of attraction or repulsion between them. The law states that the electric force is directly proportional to the product of the charges ($q1 \times q2$) and inversely proportional to the square of the distance between the charges (r^2). The force is a vector quantity, meaning it has both magnitude and direction and is defined by:

$$\mathbf{F} = \frac{k \times |q1 \times q2|}{r^2}, \tag{1}$$

where, in Equation (1), F is the electrostatic force in Newtons (N), k is Coulomb's constant, approximately $8.99 \times 10^9 N \times m^2/C^2$, $q1$ and $q2$ are the magnitudes of the charges of the two particles in Coulombs (C). r is the distance between the centers of the two charges in meters (m). The Coulomb's law is a base for advanced topics on electromagnetism. On the other side, Faraday defines the EF as imaginary lines representing the direction and strength of the EF at any point in space. The representation has different rules to show this behavior, including the lines never intersecting each other, perpendicular to the surface of the charge, and the start point of the field lines at the positive charge and ends at the negative charge.

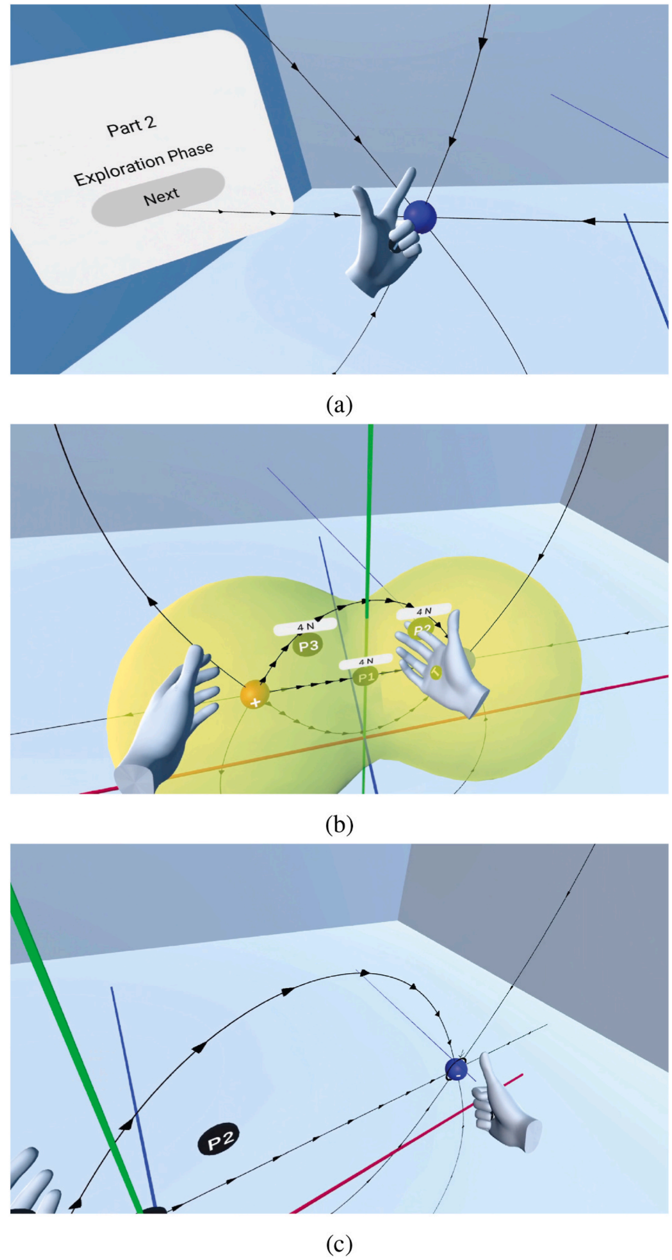


Fig. 1. Immersive virtual reality (IVR) interactions: (a) the participant explores the simulation by grabbing a particle and moving around, (b) the study participant explores an electric field value at the interest point P2, resulting in interactions between the positively (+) and negatively (−) charged particles, and (c) the study participant moves a particle on the indicator in the simulation area to define a new particle configuration.

3.4. Proposed features

In the designed IVR experience, virtual manipulatives (interactable visualization) are essential for the simulation interaction and the participants' possible inputs. The interpretation and use of these manipulatives can enable learning based on the participants' actions or affordances (Dalgarno & Lee, 2009). Previous studies have reviewed virtual manipulatives' affordances vis-à-vis learning science-related concepts (Zacharia & Michael, 2016). In the context of EFs and CPs, we delimited the included functionalities and the expected interactions (see Table 1), and we hypothesize that the features will help to improve the participants' conceptual understanding.

4. Research questions

We based the research on using IVR for education. Specifically, we provide new learning experiences for teaching and learning about EFs and CPs supported by embodied learning. Based on our designed intervention, this study aims to answer the following research questions.

- **RQ1:** How do embodied principles and IVR enhance the conceptual understanding of complex topics in STEM, such as electromagnetism?
- **RQ2:** What affordances do participants identify based on the visual and haptic feedback on the designed IVR experience?

Considerable research has been conducted on VR as a training tool. Regarding STEM-related topics, VR can provide an alternative for participants to access educational content in an immersive learning environment (Radianti et al., 2020). Such experiences should be designed carefully to promote learning (Johnson-Glenberg, 2019). To that end, the embodied principles provide a framework to align the design of VR interactions with enhanced learning (Abrahamson & Lindgren, 2014). We designed our IVR intervention based on the principles to promote a conceptual understanding of EFs and CPs. We expect that the participants will use our tool to validate their assumptions or change their previous conceptions about the phenomenon of electromagnetism. On the other side, we have affordances that describe the relationship between the properties of an intervention and the learner's actions to enable learning (Dalgarno & Lee, 2009). Our design intends to provide participants with multiple elements to promote their conceptual understanding, such as visual and haptic feedback on the IVR experience. We expect that participants will take advantage of the designed features to achieve greater learning, which could help scaffold their conceptual understanding. In addition, we expect that participants who use affordances based on haptic feedback will learn more than those who do not.

Table 1
Functionalities and interactions integrated into the designed IVR experience.

Code	Functionality Description	Designed interactions
A1	Allows the participants to manipulate the virtual CPs by interaction through the virtual hands	The participants can grab, hold, move, and release the particles in the virtual environment.
A2	Allows the participants the ability to use their bodies for learning. The participants' hand movements are required to complete the expected activities in the IVR environment.	The participants must move their hands around the virtual environment to complete the simulation activities.
A3	Allows the participants to visualize the EF lines around the simulated CP interactions.	The simulation in real time includes a visual representation of the EF.
A4	Allows the participants to identify the electric force direction and intensity using arrows over the EF lines.	The visual representation of the EF also includes several arrows over each line to represent direction. Additionally, the intensity of the EF is expressed through the number of arrows shown in the simulation.
A5	Allows the participants to visualize the electric force by including the exerted force value over an interest point (IP).	The IP provides feedback with a numerical value because of the exerted EF at that position.
A6	Allows the participants to identify the electric force intensity through haptic feedback by the vibration of the VR controllers.	The simulation area includes mapping the exerted forces on the simulation setting. The participants' hand position (inside the simulation area) activates a vibration on the controllers with an intensity according to the force exerted at that position.
A7	Provides the participants with guidelines to indicate the next position of the particles during the experimentation phase.	The guidelines indicate in which position the particle needs to be placed to do the comparison. The guidelines will trap the particle until both particles are successfully placed.
A8	Provides the participants with a questionnaire on the 3D environment to evaluate their knowledge about the explored scenes and to keep the sense of immersion during the VR interaction.	Questions are included in the virtual environment. These questions are represented by user interface (UI) menus and buttons to manage and visualize the questionnaire. Multiple choice and open-ended questions (voice recording) are included in this evaluation.

5. Methods

We conducted a qualitative study to evaluate the designed VR application. This study also compared two types of feedback using a between-group method: visual feedback (V) and simultaneous visual and haptic feedback (V + H). Participants were randomly assigned to one of the two conditions for this study.

5.1. Context and participants

We conducted our study in our university's laboratory setting. We recruited eight study participants with technology and graphics-related backgrounds with some or no previous knowledge of electromagnetism concepts (e.g., Coulomb's law) from high school or introductory college physics courses (see Table 2). Considering the specific and narrow objective of the conducted interview, which is to capture participants' predictions and explanations of their interactions with the IVR application, we anticipated that the selected sample size would be sufficient to reach saturation for a thematic analysis (Malterud, Siersma, & Guassora, 2016; Braun & Clarke, 2019).

We asked the study participants if they felt confident about understanding the concepts of EFs and CPs (Strongly Agree, Agree, Neutral, Strongly Disagree). Of the sample, one participant felt confident about his knowledge of EFs and CPs (Agree), four felt neither confident nor not confident (Neutral), and three did not feel confident at all (Strongly Disagree).

5.2. Materials

5.2.1. IVR interface

We developed our IVR interface through the Unity (C\#) and Oculus Integration library (https://github.com/PedroAcevedo/Embodied-IVR-Charged-Particles). On the IVR application, different particle settings can be shown. The elements comprising the simulation in the IVR experience are the CPs represented as 3D spheres with an assigned color based on the charge (red for positive, blue for negative), the EF lines displayed as 2D lines around the particles, the equipotential surface defined as a 3D mesh around the CPs (where the EF has the same effect), and the IPs. These IPs act as a test charge or point of reference specifying the exerted force on a 3D coordinate in the simulation area. In each particle setting, we placed three IPs in the scene.

We divided the IVR experience between rooms that encapsulate the IVR environment.

- **Introduction room:** Here, the participants initially explore the 3D environment and follow instructions to help them become familiar with the IVR experience. Specifically, the participants have an initial view of the elements that compose the simulation, such as the

Table 2
Demographic backgrounds of the eight participants recruited for the study.

ID	Condition	Gender	Level	Academic Major	Prior Physics Experience		Prior VR Experience	Confident about EF and CP Knowledge
					High School	College		
S1	V	Male	Junior	Animation and Visual Effects	AP Physics	Electric and Magnetic Interactions	Yes	Agree
S2	V	Male	Junior	Animation and Visual Effects	AP Physics	General Physics	Yes	Strongly Disagree
S3	V	Male	Freshman	Visual Communication and Design	No Courses	No courses	Yes	Neutral
S4	V	Female	Freshman	Animation and Visual Effects	No Courses	No courses	No	Strongly Disagree
S5	V + H	Male	Junior	Animation and Visual Effects	Yes	Modern Mechanics	Yes	Neutral
S6	V + H	Female	Junior	Game Development and Design	AP Physics	General Physics	Yes	Neutral
S7	V + H	Male	Junior	Animation and Visual Effects	No Courses	General Physics	Yes	Neutral
S8	V + H	Female	Sophomore	Animation and Visual Effects	Yes	General Physics	Yes	Strongly Disagree

particles and the haptic feedback. The participants should be able to interact by grabbing, pointing, and clicking UI elements.

- **Simulation room:** the participants can explore the simulated CP phenomenon. The main interactions of our designed experience occur in this room. The particle configurations are presented in sequence. For each particle configuration, the participants should complete three phases (see Section 5.2.4). An action describes a phase the participant should follow to interact with the current setting in the 3D environment.
- **Questionnaire room:** the participants respond to a virtual questionnaire. Once the participants explore one of the particle's settings, the system places them in front of a questionnaire, asking them about their previous activities. This includes multiple-choice questions (see Fig. 2a) that need to be responded to by UI interaction through raycasting. This physics function projects a ray into the scene. It returns a Boolean value if a target was successfully hit (i.e., allowing the participants to interact with the UI elements in the IVR). There are also open-ended questions (see Fig. 2b) requiring the participants to provide their answers via voice recordings.

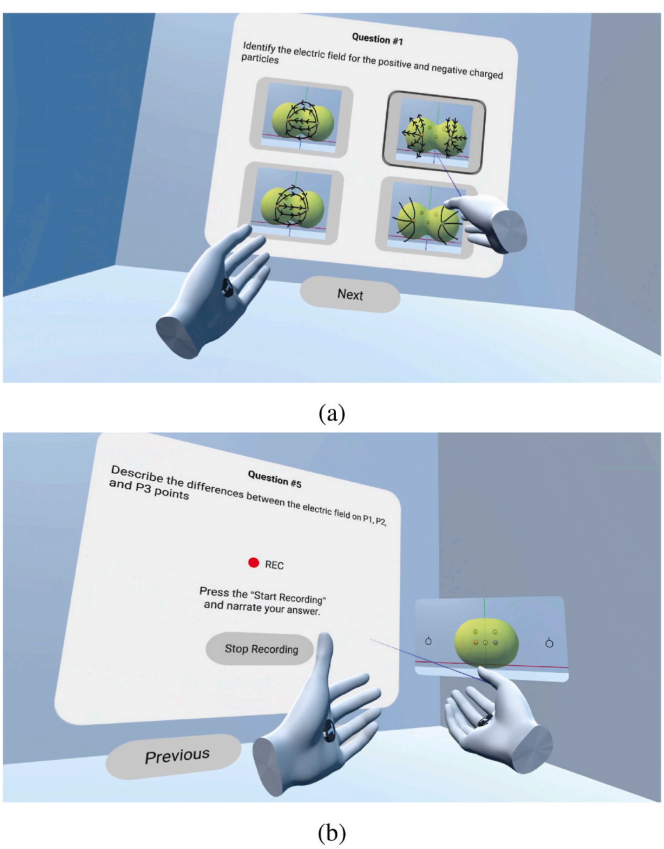


Fig. 2. Questionnaire room example: (a) the participant selects an option on a multiple-choice question, and (b) the participant records their answer to an open-ended question.

5.2.2. *Haptic rendering*

As mentioned in feature A6 in Table 1, the IVR experience includes a haptic feedback component. This haptic feedback maps the electric field intensity exerted in any coordinate point in the simulation area. The haptic rendering is obtained as follows.

- We considerate a point in the coordinate (x, y, z) as a test particle with charge 1.
- We calculate the exerted electric field on the test particle by each particle in the scene
- We sum all the forces and obtain a value in newtons.
- We repeat this calculation on all the positions in the 3D cube that encapsulates the simulation.
- We use a min-max normalization for all points in the grid to have values between 0 and 1.
- We used the values on the vibration controller, so each point in the grid has an associated vibration intensity.
- Once the center of the users' hands is around a position (x, y, z), the controllers vibrate with an intensity stored for that specific position.

5.2.3. *Apparatus*

We used the Meta Quest 2 as the input device for the IVR experience. The head-mounted display (HMD) provides an 1832×1920 per-eye LCD panel with a 90Hz or 120Hz refresh rate, and it features inside-out position and rotation tracking using four integrated cameras. Additionally, it includes two hand-held Touch controllers with haptic feedback and analog thumbsticks. The HMD was connected to a Lenovo laptop with an Intel Core i7-12700H CPU, NVIDIA GeForce RTX 3070, and 16 GB of memory.

5.2.4. *Worksheet*

During the IVR experience, the participants explore four particle configurations, which are: (a) two positively charged particles; (b) two negatively charged particles; (c) one positively charged particle and one negatively charged particle; and (d) three particles, one positively charged and two negatively charged, as shown in Fig. 3.

A scene in the simulation environment presents one of the particle configurations to be explored and comprises phases or activities (see Fig. 1). The scene's phases are defined as follows.

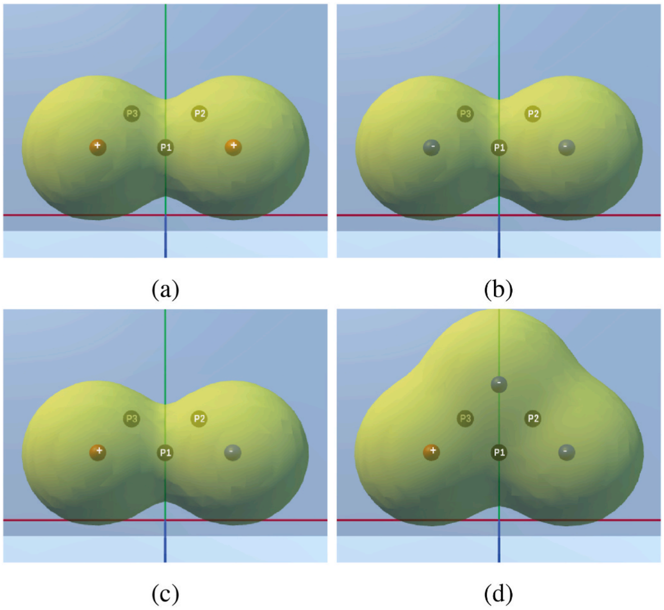


Fig. 3. Charged particle settings with changes between the charged signs and the number of particles: (a) positive particles, (b) negative particles, (c) one positive particle and one negative particle, and (d) one positive particle and two negative particles.

- **Exploration phase:** The particles are placed and can be moved around without restriction. In this phase, the participants have no task, so they can grab the particles and familiarize themselves with the simulation.
- **Experimental phase:** The particles are static, so the participants cannot grab them. We ask the participants to explore the IPs in the simulation area. We expect the participants to see the value or feel the vibration at each point.
- **Interactive phase:** The particles can be moved freely. In this phase, the participants should explore the IPs in two situations—when the particles are closer and when the particles are far away. Indicators in the simulation area are placed to specify to which position the participants should move the CP (closer or farther). The participants should move the particles to those indicators and then analyze the respective IP values.

5.3. Procedures and data collection methods

This study consists of three main steps: the pretest, experimentation with the IVR environment, and the posttest, as shown in Fig. 4. We recruited undergraduate students from the Polytechnic Institute of our university, expecting that they would have some familiarity with the concepts of CPs and EFs from previous courses or high school. However, proficiency in the topic was not a strict requirement. Participants also needed to feel comfortable using VR, as the session involved using an HMD. We included filters such as not being prone to nausea in VR headsets and being able to read English. Initially, we gave the participants a printed copy of the pretest questionnaire to complete. This test contained conceptual questions, the purpose of which was to assess the participants' previous knowledge of the EF and CP concepts. We included demographic-related questions to describe the explored population. Next, the participants proceeded to experiment with the VR simulation. We provided the participants with the required VR equipment: an Oculus Quest 2 with a controller for each hand. We asked the participants to become familiar with the 3D environment and explore four simulation scenes (see Section 5.2.4). Each scene included one particle configuration, and the participants completed a short questionnaire in the virtual environment after each of them.

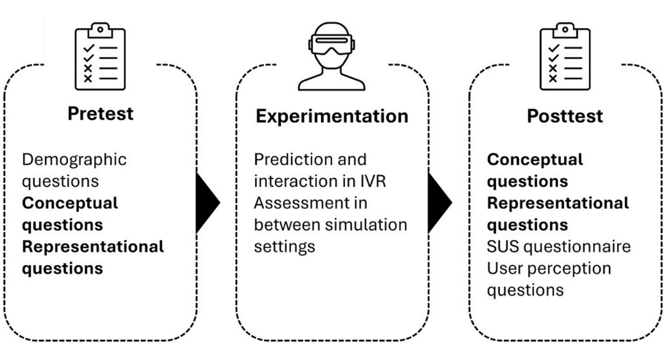


Fig. 4. The procedure for the data collection process.

During the experimentation, in the initial scene, we asked the participants to predict and explain verbally the results of their interactions. Table 3 lists the interview questions and target group. The interview consisted of asking questions about the participant's interaction with the particle configuration (two positive CPs), as we expected the participants to understand the intended activity after this scene.

After each scene in the experimentation, a questionnaire on the previously explored configuration is presented (example in Table 4). The experimentation questionnaire is structured according to the scene phases to record the participants' understanding of factors such as force interaction, distances, and charge polarity in the IVR environment.

Finally, we provided the participants with the posttest questionnaire, which included the same conceptual questions as the pretest. The posttest consists of the SUS questionnaire and some delimited user perception questions to record the participants' opinions and suggestions about the designed IVR lesson.

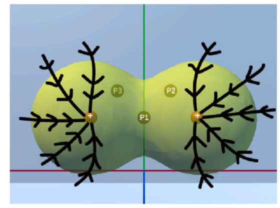
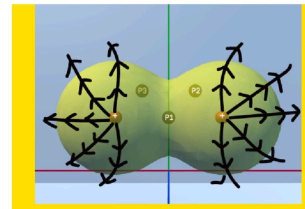
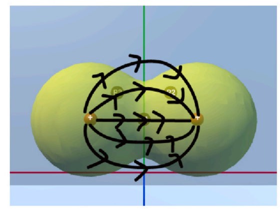
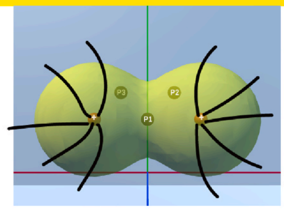
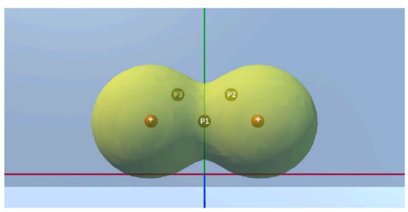
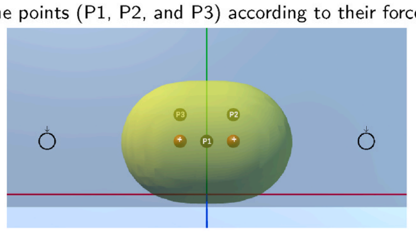
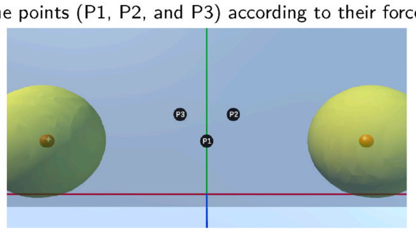
5.4. Data scoring and data analysis methods

The data analysis method employed a qualitative approach taken from Braun and Clarke (2006) six phases of thematic analysis. We coded the interviews and derived categories based on participants' responses and the purpose of the questions. Initially, we read and re-read the transcripts, noting our preliminary thoughts. We systematically coded relevant data, transferring it to a coding sheet organized into three columns: the question/context of the excerpt, the full unedited excerpt,

Table 3
Interview questions to assess the participants' perceptions of the designed IVR experience.

Treatment	Interview Questions
Initial IVR interaction	
V and V + H	What do you notice in the particle simulation in front of you?
V and V + H	What do you think will happen if you move one of the particles?
V and V + H	What happens when you place one of the particles in another position?
V and V + H	Are there any changes in the electric field lines when you move the particle?
Only V + H	What do you feel when you move your virtual hand close to the particle simulation?
Only V + H	Which property of the electromagnetism phenomenon is represented in this vibration?
V and V + H	What happens when you place your hand on one of the interest points?
Only V + H	What did you feel when you placed your hand on one of the interest points?
V and V + H	What happens in the simulation when you place the particles close to each other?
V and V + H	What happens in the simulation when you place the particles far away from each other?
End of IVR interaction	
V and V + H	From the previous scenes, which factors influenced the electric force value on the interest points?
V and V + H	What were the main differences between the scenes?

Table 4
Questions on the experimentation questionnaire for Scene 1 with positively charged particles (correct answers are highlighted in the table).

Code	Question	Choices	
EQ1	Identify the electric field lines for the two positively charged particles.		****
			
EQ2	 Rank the points (P1, P2, and P3) according to their force value.	P1 >P2 >P3	P2 = P1 >P3
		P3 = P2 >P1	P1 = P2 = P3
EQ3	 Rank the points (P1, P2, and P3) according to their force value.	P1 >P2 >P3	P2 = P1 >P3
		P3 = P2 >P1	P1 = P2 = P3
EQ4	 Rank the points (P1, P2, and P3) according to their force value.	P1 >P2 >P3	P2 = P1 >P3
		P3 = P2 >P1	**P1 = P2 = P3**

and the corresponding code (see supplementary material for an example). We then merged similar codes and searched for potential sub-themes, which we reviewed to ensure alignment with the codes and participants' excerpts. We refined these sub-themes to develop themes, and finally, we selected compelling excerpts to support the identified sub-themes and themes.

We extracted the participants' responses and arguments from their laboratory reports. A criterion was defined to validate the participants' conceptual understanding of the EF and CPs concepts. Regarding this criterion, we expected the participants' arguments to include the following.

- the relationship between the exerted EF and the distances between the particles,
- the relationship between the exerted EF and the charge of the particle setting (e.g., when the values cancel or not),
- the relationship between the CP type and the EF lines' representation (e.g., inwards or outwards), and
- the perception of the EF interaction based on the equipotential surface.

To analyze the participants' actions, we coded the screen-captured data for their performance (e.g., points of attention and hand movements during the experiment). The codes aimed to capture the participants' actions during their work with the IVR tool. We reviewed all the codes for consistency in the data collection procedure for each transcript in the study.

6. Results

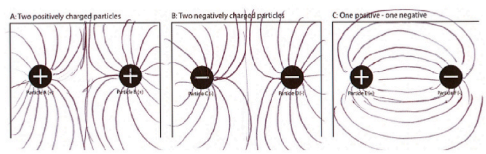
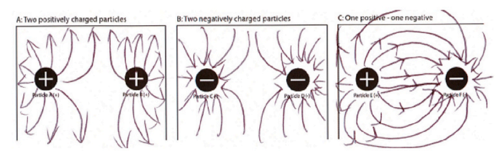
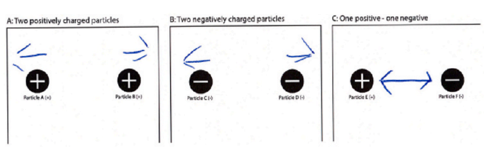
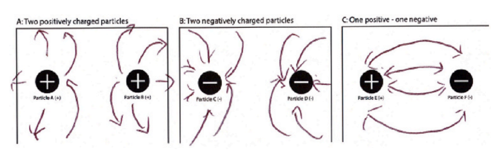
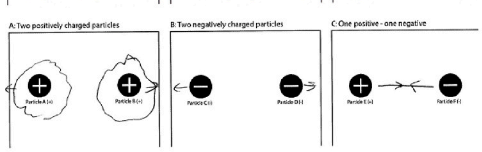
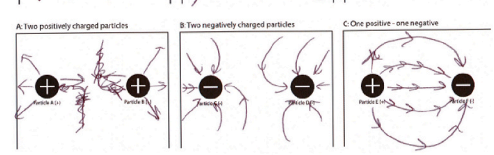
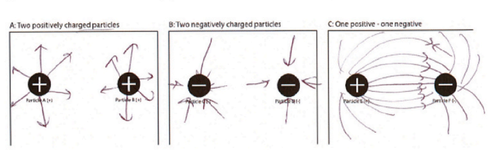
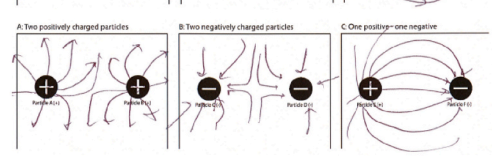
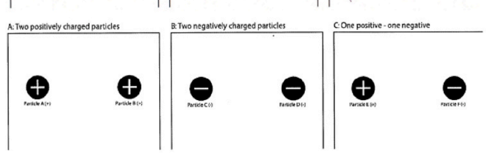
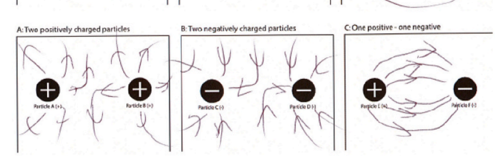
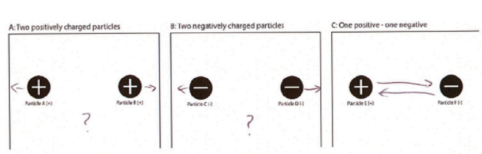
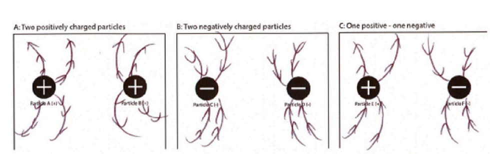
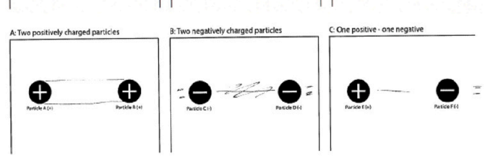
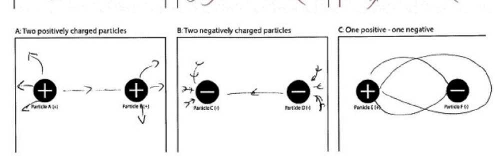
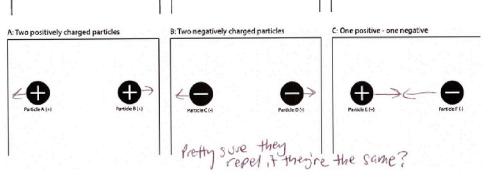
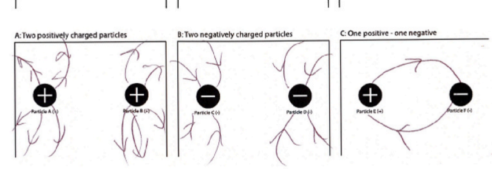
We organized the data based on the participants' confidence in their knowledge of the concepts of EF and CP. The classification allowed the participants' data to be divided into three groups: (a) Group 1: S1, the only participant that indicated "Agree" about their confidence regarding their knowledge of the topic; (b) Group 2: S3, S5, S6, and S7, who considered themselves "Neutral" regarding their knowledge; and (c) Group 3: S2, S4, and S8, who were not confident about their knowledge of the concepts.

6.1. Pretest and posttest results

On the pretest, we delimited different questions about the representation of the line in different particle settings and the EF exerted force. For questions about drawing the EF lines, the results for Group 1 showed a clear understanding of the concepts, with an accurate representation of the EF lines according to the particle scenario, only without considering the direction (arrows) of the lines (S1). The responses of Group 2 have different characteristics. The participants showed only the relationship between the particles based on the force (S3 and S5), or they did not answer the question (S7). In contrast, one participant correctly included the EF lines representing the direction of the EF (S6). Group 3 responses show an approximation of the interactions of the forces between the particles representing the lines by arrows pointing in or out based on the scenario (S2 and S8) or even connections between lines without meaning (S4).

On questions about the argument regarding the exerted EF at reference point P, Group 1 responses were accurate and considered factors such as distance, polarity, and the influence of the particle (S1). Group 2 responses included the force relationship between the particles without

Table 5
Pretest and posttest comparison of responses about EF lines acting in different particle configurations per participant.

Study participant	Pretest	Posttest
Group 1		
S1		
Group 2		
S3		
S5		
S6		
S7		
Group 3		
S2		
S4		
S8		

mentioning point P (S3) or considering point P and the force exerted by the particles (S5 and S6) using an assumption of a test charge with different magnitudes depending on the scenario (S5). Group 3 responses described the interactions of the forces without considering point P (S2) or through connections based on the particle's charges (S4). Others thought about the intensity of effects exerted by the particles at the reference point but included question marks at the end of each question (S8).

In terms of the posttest, Table 5 presents the comparison between the pretest and the posttest EF lines drawn per study participant. In Group 1, the participants had an equal representation but included the arrows to represent the direction. In Group 2, the model is improved in all cases compared to the pretest by including direction using the arrows, EFs lines properties based on the particle sets, and leaving no questions unanswered (S7). In Group 3, the participants responded to the questions appropriately by including lines and arrows in the correct direction. However, they had an incorrect interpretation of the opposite scenario in which all the lines drawn were incorrect.

Regarding the EF force interpretations, in Group 1, the participant mentioned the EF direction and the stronger influence according to the different scenarios. In Group 2, the participants said the distance and the position of the reference points were factors in the effect or impact of the particles (S5, S6, and S7). Other participants did not include point P in the explanations (S3), and most of the participants provided short answers to the questions, that is, responses of less than two sentences (S3, S5, and S7). Group 3 participants described the exerted forces based on the particle's positions on the reference point P (S3 and S5). Only one participant provided short answers without considering point P (S8). Fig. 5 presents the changes in the pretest answers—multiple-choice options grouped by the objective compiles the questions.

6.2. Interview results

We asked the participants to interpret and predict their interactions with the IVR environment during the interview. The interview was coded, and the categories were subtracted based on the participants' responses and the intent of the questions based on the thematic analysis method (Braun & Clarke, 2006). The interview responses, presented in Table 6, are generally reported rather than in groups for an overall summary of the experience with the IVR tool.

6.2.1. Confidence level

The participants' confidence in their knowledge of the EF and CP concepts was essential during their experimentation with the IVR.

6.2.1.1. Previous conceptions. The participants' confidence was

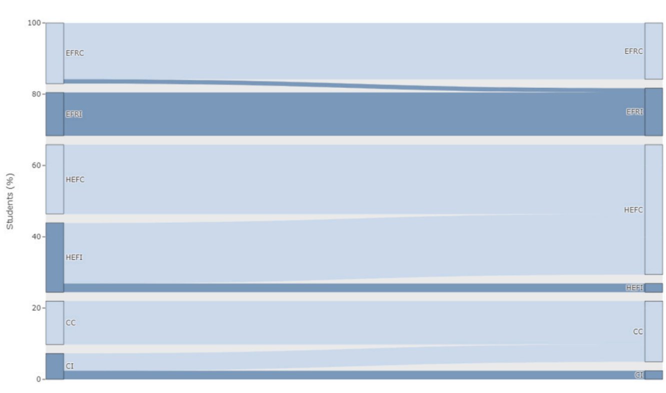


Fig. 5. Changes in responses on participants' pretest answering the multiple-choice questions. EFRC: EF on region, HEFC: higher EF in the different scenarios, C: comparison between scenarios. At the end of each label, C and I mean correct response and incorrect response, respectively.

Table 6
Theme, category, and examples extracted from the interview.

Theme	Category	Example
Confidence level	Previous conceptions	"Which property? Of what? I have actually no idea. Well, I don't think I do know the answer." (S6)
	Understanding guidelines	(Particle static at this moment.) "Where? Oh. Trying to move it. I can't." (S4)
Interpretation and assumptions	EF measure	"So, I assume if it were just P3 right here, the energy here would be 4N (assume that's newtons), and then the same would go for P2 and P1." (S2)
	Particle interactions	"The other one (particle) would move away from it due to them both being positive." (S5)
	Field lines representation	"Forces, just like, apparently like pushing away when it's like coming together." (S6)
Tool features	Feature description	"The closer I am to the particle, the stronger the vibration." (S5)
	Reactions	"That's so cool, dude. OH, that's so cool." (S1)

reflected in how they answered questions about the interactions in their IVR experience. We asked the participants to interpret and predict, so guessing about the simulation's behavior was the right approach, even though some participants needed clarification about what to expect or what they saw in the simulation environment. Statements such as "With the two separate lines going up and down as well, but they are more curved. I don't know how to explain that like …" (S5) or "It does like change the direction of the force, I mean, like not the force, like the direction. Itself, but like the angle of the force, I guess" (S6) reflects the uncertainty of the participants' answers. In addition, phrases such as "That makes any sense?" (S5), "I don't know." (S6 and S8), and "I guess" (S6) demonstrate that the participants were not confident about the correct answer. As a specific example, for the question "Which property of the electromagnetism phenomenon is represented in this vibration?" for condition V + H, three out of four participants who were asked this question responded that they did not know the answer. One said, "The thing about how two positive charges repel away from each other" (S7), referring to the EF as a "thing" but with a sort of explanation of what the vibration represented.

6.2.1.2. Understanding the guidelines. The IVR activities were guided, and the participants indicated what actions needed to be done on the simulation in each phase. Most participants understood the guidelines, but others required help to begin their interaction. Specifically, when the particles are indicated as static, the participants try to grab and move them. One participant faced difficulty, stating "Where? Oh. Trying to move it. I can't." (S4). At the moment when the particles are closer and fixed by the indicator in the scene, one participant exclaimed, "But if I drag it closer … Come on." (S3). The participants got confused when the IPs were introduced because they had not found out what they were, what interaction was needed, or where to put their hand at the initial moment; one participant stated, "I can't move the points. I can't." (S7), and another said, "Is that the uh sphere around it? Interest Point. Where would that be?" (S2). In contrast, some study participants could infer what the IP is in the scene, saying "I'm assuming the P1 is the interesting point …" or "All right, I've seen the highlight areas. There's the P1 where the max force is being applied" (S3).

6.2.2. Interpretation and assumptions

We delimited the interview questions to fit the participants' interpretation of the simulation affordances.

6.2.2.1. EF measure. The EF included in the simulation, which represents the force exerted by the particles on the IPs, is one of the main activities in the IVR. The participants were asked to explore them and to identify/feel the force exerted on those specific points in the scene. From the participant's interpretation, the EF is explained from different perspectives, such as "force on each particle in Newtons" (S1), "The way they repulse each other" (S5), "scale of the force" (S6), "the energy" (S2), "It is how it's being affected" (S7), and as an "N force" (S3). In addition, the connections between the exerted EF and the changes made in the simulation (e.g., change a particle position) were described as follows: "They're the fields completely separate … no Newtons on them" (S5), "When you get close to each other, you can kind of like see a big increase in the energy here" (S2), and "I see the N force changing in the center and in P2 as they're further away" (S3). For the group V + H, the mapping for the vibration and the shown value on the IPs was recognized, with participants saying such things as "P1, P2, and P3 have no vibration" (S2), "So, like it says like 0 and that means like no force. So, I don't feel any vibration" (S6), and "For P3 and 2, they start to vibrate a bit, and for both of them, they both say 4 N" (S5).

6.2.2.2. Particle interactions. These interactions are the main objective of the simulation environment, and how the participants infer and describe the simulation is essential. The equipotential surface generated by the CP is included in the simulation. The participants recognized it in different terms, such as "3D mesh" (S1), "a peanut" (S5), "yellow spheres" (S7), "force field" (S6), and "soil splitting from each" (S3). Other related factors related to particle simulation are the distances and the exerted force relationship. The participants stated, "If I move it away from each other like far from one another … it'll be like, less strong in general" (S6), "But the P forces change depending on their location" (S5), and "They're so far apart, they're not getting any N force on them" (S5). In addition, the relationship between the distance and the equipotential surface was recognized, with participants saying things such as "In this case, because I moved them too far apart, it became split" (S1) and "change like the way that the circles like are merged or not merged" (S8).

6.2.2.3. Field lines representation. Other main elements of the designed simulation are the representation of EF lines and their relation to the particle setting presented in the IVR. The participants noticed these lines, saying things such as "forces trying to move away" (S3), "forces, just like, apparently like pushing away "(S6), "field lines" (S1), and "lines coming off' (S7). In addition, the participants talked about the direction and the ways the curves of the lines were displayed in the simulation, saying things such as "like coming together" (S6), "they appear to be going towards each other" (S4), "trying to jot off in one of these directions" (S3) and "It goes straight and then goes straight up, and then the one on the right will go straight but then goes down" (S4). On the EF lines, the direction is included based on the particle setting (arrows pointing out or in). The participants recognized these as the forces and how they could interact with the particle. The participants made comments such as "then the arrows are much shorter" (S5), "where the arrows are going away from each other" (S4), "there are arrows going out from each" (S8), and how this arrow could change by "change the way that the arrows are or the frequency of them" (S8).

6.2.3. Tool features

Some participants focused on describing what the IVR tool provided as feedback to their interaction rather than reacting to the meaning of this feedback for the simulated phenomenon. In this section, the noticeable features of the IVR tool are described through the participants' explanations and responses.

6.2.3.1. Feature description. The participants described the simulation features, where they were asked to point to the elements in the scene or explain the changes to their actions. For the EF lines representation, one participant said about the differences "… and it is in real-time" (S1) due to the lines on the IVR being updated in each frame when a particle changed its position. Regarding the IPs, one participant described their behavior by saying, "I put my hands on them, they updated" (S1). Regarding the displayed value, the participants commented, "P1 says 0 N, P3 says 4 N, and then as well as P2 says 4 N" (S4), "It shows me. I'm assuming this is a measurement." (S8) and "I'm seeing the numbers as a 0 N, 4 N and 4 N" (S3). The equipotential surface is defined to be updated once the particle setting is configured (once the particle is static again). This feature was used to explain the phenomenon, with participants saying things such as "Shifts the yellow part or it disconnects entirely." (S7) and "I put the other one next to the other one, and they kind of like form one big like a yellow sphere around it" (S2).

For condition V + H, the participants were asked to describe their feelings during their first simulation interaction. They made comments such as "It starts vibrating." (S7) and "… and it vibrates." (S8). The participants included the vibration as a factor to explain their arguments and to show the relationship between this vibration intensity and the exerted force on the IPs, saying things such as "Points 2 and 3 start showing 0 … and it stops vibrating at the points." (S7) and "The closer I am to the particle, the stronger the vibration." (S5). Regarding this vibration property, one participant said, "Actually, the whole thing just vibrates when I go near it. I don't really know if I'm accidently touching the …" (S8); in that case, the participant focus should be on the IPs. However, the simulation vibrates around the surrounding area of the particles according to the force exerted on each of the points in the 3D environment.

6.2.3.2. Reactions. Although the interview was not intended to be a think-out-loud session, the participants provided their reactions at some moments during the IVR experience. These reactions were positive, with participants commenting "That's so cool, dude. Oh, that's so cool." (S1) and "That's very neat." (S4). Other participant reactions indicated that participants connected the visual elements and the given instructions, for example, "Oh, I got it now. OK. Oh …" (S5) and "All right, so I'm moving these to P1 and P2. Yeah, I'm seeing a drastic change." (S3).

6.3. Experimentation questions

The questions are based on the EF force exerted on IPs and the representation of EF lines. Table 7 shows the results of the multiple-choice questions by group and participant. In general, the participants responded to most of the multiple-choice questions correctly. There were minor errors in the ranking of the EF at the IPs, and only two participants (S3 and S2) failed on questions related to the EF lines representation (see Table 8).

Additionally, we asked open-ended questions to collect the participants' explanations for the phenomenon's interaction with the resulting exerted forces and the difference between them on the IPs. A summary of the participants' responses is presented in Table A1. The participants recognized the influence of the number of charges, their polarity, and the distance as factors influencing the exerted EF.

6.4. Video data

Multiple behaviors and patterns have been recognized from the screen recording of the participant's performance in the IVR environment. The expected actions during the experiments were repeated between the scenes; the participants moved directly to the simulation's center to grab the particles, moved them in different directions around the axis to visualize the real-time changes on the EF lines, and split the equipotential surfaces. The participants used their dominant hand to move the particles; only in exceptional cases did they use both hands, such as when the particle was on the other axis or needed to be moved to the farther indicator (experimental phases). This interaction can be divided into two cases. Some participants preferred to use both hands

Table 7
Experimentation with multiple-choice questions: answers per group and participant.

ID	Scene 1				Scene 2				Scene 3				Scene 4				Total
	EQ1	EQ2	EQ3	EQ4	EQ1	EQ2	EQ3	EQ4	EQ1	EQ2	EQ3	EQ4	EQ1	EQ2	EQ3	EQ4	
Group 1																	
S1	1	1	1	0	1	1	1	0	1	0	1	1	1	1	1	1	81.25
Group 2																	
S3	1	1	0	1	0	1	1	1	1	1	0	1	1	1	1	1	81.25
S5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100
S6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100
S7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100
Group 3																	
S2	1	1	1	1	1	1	1	1	0	1	1	0	1	1	0	1	81.25
S4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	93.75
S8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100

Table 8
Summary of main arguments for experimentation questions per participant.

Study participant	Main factors relating to the EF	Difference between scenes
S1	"Positioning and distance relative to each charged particle affect the electric force."	"Charged particles are being used."
S2	"The increase or influence of the electric force on the interest points would be the space between them."	"See a difference when it comes to electric force as well as the fields around it and which kind of charge you have."
S3	Response not recorded.	"The main difference, I guess, is the interactability. You see the forces and how they move and interact with each other depending on the position."
S4	"The distance, as well as the type of particle, has an effect on the electric force value on interest points."	"The main difference, I would say, is the different particles involved within each scene."
S5	"Direction or charge of the particle, the charge of the secondary particle as well as the distance between the particles."	"The complexity of the arrows showing the forces gets more complex as you add another secondary negative particle."
S6	"The distance between two particles is definitely one of the factors that influenced the force value, and it's also the poles of charged particles that are interacting."	"So those are the main differences between the distances and the charges of the particles."
S7	"Factors that influence the electric force value on the interest points are how close they are to the centers of the fields and how close those points are to each other, which ones are positive and which ones are negative."	"The main difference between them is that the ones where it was two of the same charged particle lines liked to repel away from each other … where there were three of them, one positive and two negatives, all the lines in the positive one were going towards the negative one, and then points were greater in value."
S8	"Distance influences the electrical force value on the interest points as well as what particles are around."	"The main differences between the scenes are the charges of the different particles, and then obviously, the last scene has three particles, so it functions very differently than the previous three."

and keep the point of view static (S1, S7, S6), and others moved the point of view and used their dominant hand to carry out the interaction (S2, S4, S8). Most study participants used hand movements during their voice recording explanations of virtual hand actions, as in a real-life environment. Regarding the IVR features, the participants used ray-casting to point out things on the images of reference to explain their points (e.g., point out P1 in the diagram). Some participants were curious to move the particles outside the boundaries of the simulation, in which case the particles would not have any surface lines around them (S3 and S7).

6.5. Perception ratings

On the posttest, the participants were asked to provide feedback and their perceptions of the IVR experience. Table 9 summarizes the participants' responses and the questions. The questions relate to tactile feedback (only V + H), visual feedback, and perceptions of the IVR experience. Additionally, we validated the tool using the System Usability Scale (SUS) (Brooke, 1996), a reliable instrument to estimate the usability of a software tool by degree of usability from 0 (poor) to 100 (excellent). We obtained a score of 75.31 for the developed IVR tool, which suggests above-average usability compared to other VR learning tools (Holly et al., 2021).

7. Discussion and implications

7.1. RQ1: how do embodied principles and IVR enhance the conceptual understanding of complex topics in STEM, such as electromagnetism?

Participants used the designed IVR tool, based on embodied principles, to learn the concepts of EFs and CPs. Comparing the pretest and posttest results and participants' statements about the experiment indicated a possible improvement in their conceptual understanding. Group 1 improved in drawing and wording used in their arguments, while Group 2 improved EF lines representation (see Table 5). These results suggest that visual cues in IVR helped (A3, A4, and A5 in Table 1) participants comprehend the concepts, aligning with findings from previous studies where visual representation was a significant affordance in understanding scientific content (Dengel & Mägdefrau, 2018). This finding aligns with the results from Reeves, Crippen, and McCray (2021), where they conducted a qualitative study exploring students' experiences using an IVR for chemical learning. The authors found that visual representation was considered the main affordance that positively influenced the understanding of scientific content. However, unlike their study, which involved multiple sessions over a semester, our study participants had a single exposure to the IVR activity. This limitation may have restricted adaptation to the tool and prolonged exposure to the topic, which is typically afforded in a regular class setting.

Regarding interactions, having control through their hands or agency was a critical factor in leveraging the interactive experience in IVR. Participants frequently commented on the feature of grabbing a particle (A1 and A2 in Table 1), highlighting the importance of the position and distance between particles. Johnson-Glenberg (2019) has identified agency as a critical affordance of IVR design, encouraging incorporating physical, kinesthetic actions that allow learners to manipulate content and take ownership of their learning. Features like A2 reflect this principle, allowing participants to use their bodies, which,

Table 9
Summary of main arguments for experimentation questions per participant.

Questions	Code	S1	S2	S3	S4	S5	S6	S7	S8
The tactile feedback provided by the controls helped me understand electric fields.	T1	x	x	x	x	Agree	Strongly Agree	Neutral	Neutral
The tactile feedback was easy for me to interpret.	T2	x	x	x	x	Agree	Strongly Agree	Neutral	Agree
The visual information provided by the simulation helped me understand electric fields.	V1	Strongly Agree	Strongly Agree	Strongly Agree	Agree	Agree	Strongly Agree	Agree	Strongly Agree
The visual information was easy for me to interpret.	V2	Strongly Agree	Strongly Agree	Strongly Agree	Agree	Neutral	Strongly Agree	Agree	Strongly Agree
Seeing the particle simulation with the VR headset was engaging.	VR1	Strongly Agree	Strongly Agree	Strongly Agree	Agree	Strongly Agree	Strongly Agree	Agree	Agree
The Virtual Reality experiment makes me understand the concepts of the electric field.	VR2	Agree	Agree	Agree	Agree	Agree	Strongly Agree	Agree	Agree
I would like to learn with this VR experiment in the classroom.	VR3	Strongly Agree	Strongly Agree	Agree	Agree	Agree	Strongly Agree	Agree	Agree

according to embodied cognition, can influence conceptual understanding, especially for those initially lacking confidence in CP and EF concepts. An example of improvement is participant S7, who did not answer some pretest questions but provided arguments and explanations on the posttest. Group 3, who had the least confidence in CP and EF concepts, provided answers using terms related to essential factors such as distance, forces, and EF effects. It is worth noting that participants' exposure to the concept through the assessment questions and IVR intervention may have helped refresh or recap their previous conceptions, enabling them to respond with appropriate terms. However, it is unclear whether the IVR or the guidance helped them achieve this connection. On the perception questions, all the participants answered "Agree" (37%) or "Strongly Agree" (62%) with the statement V1 (see Table 9), assuming that the visual cues were essential for understanding the EF concept; additionally, for the statement VR2 (see Table 9), the participants mainly stated they "Agree" (87%) that the VR experiment allows them to understand the EF concept. Previous studies have also reported acceptance of VR lessons (Parong & Mayer, 2018; Pirker et al., 2017), though factors such as the novelty effect can influence this preference (Miguel-Alonso, Checa, Guillen-Sanz, & Bustillo, 2024). However, in our study, all participants had previous VR experience, allowing them to evaluate their preferences based on the tool's overall structure and content rather than the novelty of VR.

Feedback from participants included comments like, "It was interesting to learn about something I hardly had an idea about; I now know more about it." (S2) and "My understanding of the concept definitely went up." (S8), highlighting the opportunities to learn and improve understanding through the IVR experience. However, Group 2 had fewer arguments in their posttest answers, with most participants not providing complete answers. This may indicate a decline in motivation or willingness to participate at the same level as the pretest. The average experimentation time was 28.5 min, which could have influenced this behavior. Previous research has discussed the duration of VR interventions, noting that extended use of an HMD can cause motion sickness and visual fatigue, negatively affecting participant performance (Dużmańska & PawełStrojny, 2018; Szpak, Michalski, Saredakis, Chen, & Loetscher, 2019).

7.2. RQ2: what affordances do study participants identify from the visual and haptic feedback on the designed IVR experience?

The pretest-posttest results, the experimentation interview, and the recorded questions are included. The recognized affordances, such as the EF lines representation, EF values on the IPs, particle interactions, and settings configuration by movements, helped the participants achieve a possible learning gains regarding the CP and EF concepts. All the participants (except S3) related the main factors of the simulated phenomenon and the EF calculated values, which are the number of CP, the CP polarity, and the distance, as factors influencing the exerted EF. Similar results have been found whereby affordances help participants reach learning goals, especially for this kind of science experience where the IVR affordances are offered outside the laboratory (Reeves et al., 2021), which is the case with invisible phenomena such as CPs and EFs (Strzys et al., 2018).

Regarding the affordances noticed and used by the participants in this study, all of them were recognized, as evidenced by the participants taking advantage of the simulation's interactivity to use body movements to grab particles, change particle settings, explore IPs, and feel the vibrations. Additionally, field lines representation was recognized by the participants with terms such as "electric field" (S1), "forces" (S3), or "lines" (S7). The exerted forces values shown for the IPs were described by S1, who recognized that the value appears once the hands interact with the IPs. One of the explicit components is the direction represented by the arrows. The equipotential surface output and expected feedback were pointed out by participants during the simulation interactions by saying, for example, "change the way that the arrows are or the frequency of them" (S8) and "shifts the yellow part or it disconnects entirely" (S7).

Focusing on the participants with condition V + H, participants S5-S8 were unaware of the vibration mapping in the simulation environment, even though after several interactions in the initial scene, they linked the concepts and recognized the intentions confirming the expected outcomes. Regarding the learning gains, all participants with the V + H condition obtained 100% on the multiple-choice questions in the experimentation, showing the connections between the explored scenes and the scenario comparison. More analysis is required to support the advantages of haptic feedback in IVR situations because the participants performed similarly in both conditions. Acevedo et al. (2022) conducted a study evaluating haptic feedback, even though their findings showed that having haptics did not improve learning gains, as no significant differences between the conditions with or without haptic were found. Indeed, more analysis and studies are required to improve the haptic influence on IVR designs.

Considering the explored affordances, the participants integrated their comments as suggestions at the end of the posttest. One participant suggested that the equipotential surface should be explained in the introduction to understand what this surface represents clearly. Another participant was interested in how to reset the particle settings to visualize and contrast the initial particle arrangement with different particle positions made by the study participant. Other study participants suggested the revision of the UI button menu interactions, which can be hard to click between the changes of phases during the experiment. For example, some participants had difficulty with the raycasting click, as it took them more than two attempts to press the button.

7.3. Practical implications

The design implications for educators, instructional designers, and

VR developers relate to features that could be incorporated into IVR experiences to enhance learning in STEM topics. The material, content, and learning objectives are crucial for scaffolding learning. In this context, using HMDs can uniquely engage and motivate participants. To promote affordances, we validated using virtual manipulatives for interacting with simulated phenomena, such as electromagnetism. We summarize in Table 1 the features we implemented in our IVR tool. Through interviews and screen recordings, participants could predict, interact, and utilize these features for learning and control within the simulation.

Regardless of our study focused on learning electromagnetism concepts, we aligned our proposed features as generic as possible to be able to be extended for other STEM topics. A comparison can be made with other designed embodied IVR tools (Chatain et al., 2022), in which authors delimited their interactions or used gestures specifically for their intended concept (e.g., moving hands to change derivatives output). In our case, the simulation area can be seen as the area of interest, and a particle can be understood as a single element of the simulation. Moving the element in the simulation will alter the final output; the movement should be aligned with the gestural sense of the topic, as can be separating the particles from each other or utilizing the coordinate axis to explore the influence of the distance between elements. In that sense, we can summarize the following design guidelines.

- **Enhance agency through bodily actions (A1 and A2):** Our implementation of embodied learning principles required bodily actions, such as grabbing a particle, moving it around the simulation area, and placing it in indicated positions. Participants pressed the controller's trigger button, moved their hands, and adjusted their positions to interact with the simulation.
- **Provide sufficient visual cues (A3, A4, and A5):** To communicate detailed information without overwhelming participants, we included enough visual cues in the IVR environment. These included 2D lines for EF lines, arrows for direction, specific forces for EF intensity, equipotential surfaces, and axes for indicated positions.
- **Enable haptic feedback only on intuitive interactions (A6):** This feature enhances the sense of presence and immersion. In our case, we used haptic feedback to reflect the variable intensity of EFs around the simulation area. The vibrations increased or decreased according to particle positions, clearly mapping vibration intensity and EF values.
- **Include guidelines and instructions at the right pace (A7):** Including guidelines in IVR helps participants direct their experiences. Designers must guide users through intended objectives while aligning the activity pace to ensure actions remain simple and guided, as seen in the included phases (see Section 5.2.4).
- **Include short assessments in VR (A8):** Integrating assessments into the VR environment can be beneficial for maintaining a sense of presence. However, validating this feature's effectiveness was beyond this study's scope. We recommend that assessments in VR be timed and brief to avoid extending the overall interaction time, which can negatively affect some users.

7.4. Theoretical implications

This work presents the design of an IVR experience grounded in embodied learning and embodied cognition principles (Abrahamson & Lindgren, 2014). We validated the design through a qualitative study where participants noticed and utilized the implemented features, leveraging the affordances of using HMDs and immersive learning. While previous studies have employed embodied cognition with immersive technologies as a theoretical framework (Johnson-Glenberg, 2019; Johnson-Glenberg & Megowan-Romanowicz, 2017), this study builds on a custom-made experience aligned with embodied design guidelines. These guidelines encompass activities, materials, and facilitation, including the necessary visual and haptic cues to enhance participants' conceptual understanding of the STEM topic.

The abstract nature of electromagnetic phenomena, which cannot be easily demonstrated in standard laboratory setups, provides an opportunity for computer-based simulations. IVR is particularly suited for this purpose. We consider it meaningful to develop VR experiences that extend current lab experiences rather than merely replicating physical phenomena. Simulations and interactive visualizations of invisible and abstract phenomena, such as electromagnetism, can be valuable tools in designing STEM learning experiences. Researchers have discussed the connection between abstract concepts and the use of immersive experiences in IVR design (Dede, Jacobson, & Richards, 2017). Moreover, there is a need for qualitative studies in VR and education research to explore deeper understandings of students' feedback beyond the common quantitative and self-reported measures, as noted in a recent systematic review (Lui, Not, & Wong, 2023). These major theoretical implications extend to the work of scaffolded and personalized IVR experiences for learning in STEM, including design guidelines.

8. Conclusion, limitations, and future work

In this study, we designed and developed an IVR experience based on embodied design principles to promote the conceptual understanding of FEs and CPs. We aim to encourage STEM learning and teaching through IVR, including different affordances such as visual and haptic cues. We conducted an exploratory study to identify the effect of the IVR tool and the affordances used by the participants. The results suggest that participants' learning improved with the intervention. The results show a higher score on the experimentation questionnaire and an improvement between the pretest and posttest results, as the number of correct answers increased.

Regarding affordances, the participants identified critical factors of the simulations during the interview. These include EF values at points of interest, EF lines, the intensity of arrows, and vibration mapping. In addition, factors such as distance and charged polarity were recognized during the participants' interactions.

8.1. Limitations

This study has some limitations. The sample size could be considered small to fully validate the IVR intervention's effectiveness. Additionally, iterative analysis could help ensure no new themes emerge during thematic analysis. Therefore, further studies are needed to test the proposed design. Moreover, participants required clarification regarding the guidelines, which were predominantly text-based; future iterations should integrate more visual aids to enhance comprehension of the activities. For participants less familiar with the concepts (Group 3), clearer explanations and introductory information about EFs and CPs before or during the IVR session could have improved their engagement and understanding. Furthermore, this study focused exclusively on CPs instruction, limiting its applicability to other STEM concepts. Future research should explore whether similar findings apply across diverse STEM fields and assess how the proposed design guidelines align with other embodied IVR experiences.

8.2. Future work

For future work, different delivery methods can be explored to validate the embodied benefits of IVR; for example, comparisons can be made between traditional methods using control groups. Furthermore, metrics such as time spent during lectures, cognitive load, immersion, and exposure to HMD and their relationship to conceptual understanding and learning can be explored. In this regard, research should focus on the metrics that could impact the designed IVR interventions to determine the possible effects on STEM learning in immersive environments.

9. Statements on open data and ethics

This study has been reviewed and approved by the Institutional Review Board (IRB) at Purdue University. All procedures complied with relevant laws and institutional guidelines, and the appropriate institutional committee(s) approved them.

CRediT authorship contribution statement

Pedro Acevedo: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Alejandra J. Magana:** Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Yoselyn Walsh:** Validation, Investigation, Conceptualization. **Hector Will:** Validation, Investigation, Conceptualization. **Bedrich Benes:** Supervision, Software, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Christos Mousas:** Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare non-competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Appendix A. Supplementary data

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