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The Effects of Immersion and Dimensionality in Virtual Reality Science Simulations: The Case of Charged Particles

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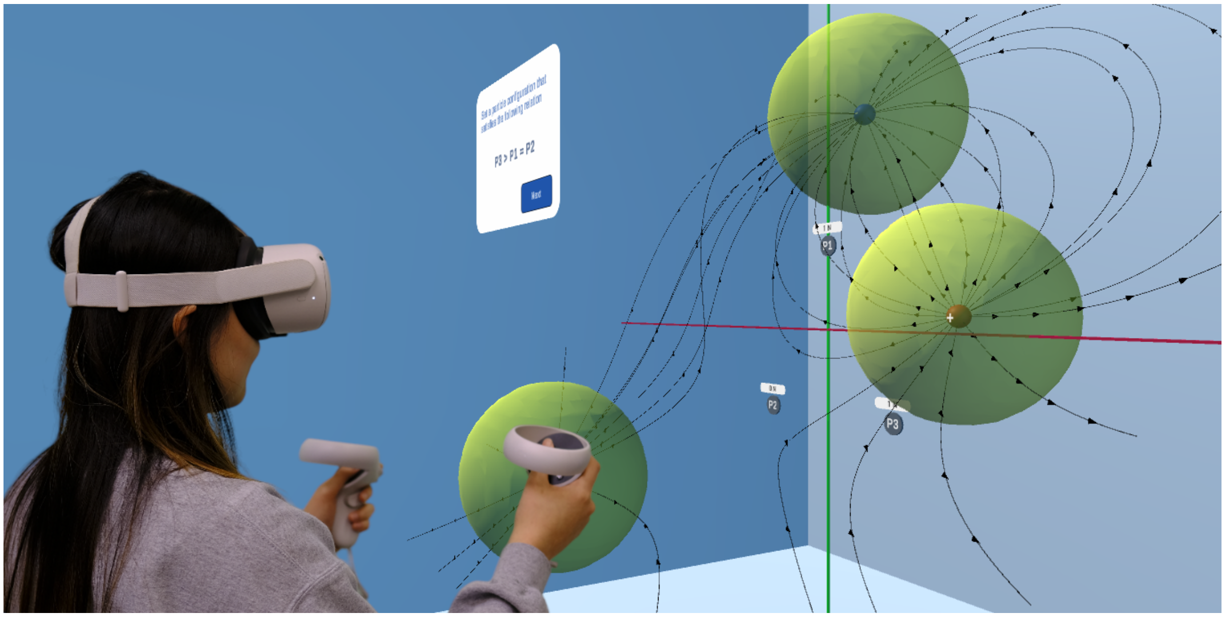

Figure 1: We developed an interactive VR simulation of charged particles where participants can manipulate the particle position and explore the corresponding fields.

ABSTRACT

Researchers have provided insights into using virtual reality (VR) for visualization and interaction with 3D models and simulations. The interaction allows users to manipulate the 3D elements and visualize changes based on their inputs from movement with controllers or spatial actions. However, some users may find this interaction overwhelming, especially when immersed in a virtual environment. Additionally, the choice of dimensionality for visualizations influences user interaction, with potential implications for immersive experiences. Thus, we conducted a 2 (Immersion: Desktop vs. HMDVR) × 2 (Dimensionality: 2D vs. 3D) within-group study ($N = 32$) to explore the impact of the utilized immersive degree and the dimensionality representation of the content on participants' experience in terms of engagement, task load, usability, skill, and emotions when interacting with a science simulation. We designed and developed an application to simulate charged particles and electric field lines. We asked participants to complete a task of changing particles by matching them to a given simulation output. Our results indicated higher workload rates for HMDVR conditions, particularly with 3D representation, compared to Desktop. However, HMDVR conditions also showed greater engagement, emotional response, and presence. Based on our findings, we argue that participants prefer HMDVR over Desktop environments regardless of dimensionality.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Computing methodologies—Modeling and simulation—Simulation types and techniques—Interactive simulation; Human-centered computing—Visualization—Visualization application domains—Scientific visualization

1 INTRODUCTION

Immersive technologies are currently trending worldwide, with numerous efforts underway to promote their adoption in daily life. Advanced head-mounted displays (HMDs) and similar products are available in the market, diminishing concerns regarding their feasibility. Consequently, the rising demand for mixed, virtual, and augmented reality applications for entertainment, training, and learning drives the development of more engaging applications and experiences [37, 73]. In virtual reality (VR) application design, selecting the interaction paradigm can influence the degree of immersion in the environment [26]. Johnson-Glenberg [33] has defined different principles and has suggested practical approaches for designing immersive virtual environments, aligning with exploiting users' agency to interact with the virtual environment, thus empowering them to orchestrate their actions and outcomes. However, not all principles are suitable for all solutions. In education, immersive VR can increase processing demands on working memory and decrease knowledge acquisition, compared to conventional media

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[47]. Users can feel VR cumbersome in entertainment due to the possible cybersickness [61]. In training, the fidelity of the replication in some conditions could affect users' presence and hinder their performance for real-world simulated tasks [49]. Therefore, when designing VR interfaces, the included features and the chosen immersive level are crucial factors to consider depending on the expected outcome, where not all features are needed depending on the purpose of the experience.

High-end HMDs enable users to move and interact with the virtual environment in six degrees of freedom (DOF), consisting of three translational (left/right, up/down, and forward/backward) and three rotational (roll, pitch, and yaw) movements [32]. Considering the six DOFs implies a challenge regarding the transfer of usual screen interactions such as the windows, icons, menus, and pointers (WIMP) or natural user interfaces (NUI) [26]. This caused the fact that there is more DOF in VR compared to 2D interfaces, generally including only two DOFs (position on the two dimensions x and y). The necessary characteristics for VR applications are an area of interest, and several researchers conducted studies to show the possible outcomes of designed interactive environments [22].

Researchers have mentioned and demonstrated various possible adverse effects of 3D technologies and VR, such as discomfort, eye fatigue, dizziness, headache, disorientation, or motion sickness [58]. Furthermore, researchers have explored the conditions, constraints, and topics under which HMDs can perform better than Desktop [72]. Indeed, in terms of VR application design, exploring how we represent the content in a virtual environment is essential, as the dimensionality of the graphics (2D or 3D) can elicit varied user behaviors regardless of the intended interactions [21, 56]. These behaviors can directly influence the expected outcomes (e.g., learning or training). To address this possibility, we conducted a study to explore how immersion (HMDVR vs. Desktop) and dimensionality (2D vs. 3D) impact participants' experience in terms of engagement, task load, usability, skill, and emotions when interacting with a science simulation. Although we could have examined several science concepts, we targeted an electromagnetism-related concept for this study due to its abstract and invisible nature. We reported complexity to learning even after instructions [46, 60]. Thus, we designed and developed an application to simulate charged particles and electric field lines (see Figure 1). Understanding dimensionality and immersion will help us develop better guidelines for designing educational VR applications.

We divided our paper into the following sections. We present the background, study objectives, and research questions in Section 2. We introduce the experiment details, such as participants, the designed simulation and features, and the research design in Section 3. We compile the results from the conducted user study in Section 4. We delimit the discussion, address the research questions, and highlight limitations and future work in Section 5. Finally, we present our conclusions in Section 6.

2 BACKGROUND AND STUDY CONTEXT

2.1 Simulations

Several researchers have developed and used simulations widely in scientific research, providing controlled environments for understanding complex phenomena that are challenging to replicate in reality, such as physics interactions [53], chemical compounds [54], and biological processes [45]. By modeling intricate systems with multiple components, simulations offer visual representations through computer-generated animations, enhancing comprehension for users with technical and non-technical backgrounds [44]. Their effectiveness lies in delimiting constrained environments, allowing precise control over inputs and outputs to study and analyze various scientific phenomena.

Computer simulations as pedagogical tools have demonstrated potential benefits for science education [10, 15]. Authors reported that using these tools with traditional instruction could enhance learning [59]. Accompanied by a structured design, simulations could arouse curiosity and interest in the students and engage and motivate them to learn, unlike other practices [1, 9, 46]. Designers generally extend these benefits to VR applications, mainly visualizing scientific simulations through immersive experiences [9, 72]. Researchers have used VR to teach science concepts and have reported positive learning outcomes [37, 39]. For instance, Pirker et al. [45] developed and evaluated Maroon VR, featuring multiple interactive physics simulations. Their findings showed the acceptance of their setup for learning about physics, considering the significant benefit of using simulations and visualizations. Similarly, Ferrell et al. [18] presented interactive molecular dynamics visualizations for chemistry education, demonstrating higher learning gains than slideshow materials. These studies promote the integration of VR simulations for science education.

2.2 Dimensionality

Dimensionality drives the features composing the design of an interactive virtual environment. The expected tasks of a virtual environment constrain the visualizations (2D or 3D) that can be effective and efficient [38]. The design choice should align with the application's intended purpose, encompassing factors such as complexity, display technology, rationale of the interactions, task, and context [16]. For instance, the choice between 2D and 3D graphics in data visualization impacts how data is understood. While 3D visualization offers varied perspectives for data analysis, 2D remains preferable for specific data types [38]. However, 3D visualization poses challenges such as object occlusion, perspective distortion, and loss of legibility of tilted graphic elements [57]. Designers should consider the interactions they aim to promote when choosing graphics for an application. Likewise, careful delivery is crucial for the application objectives when selecting the display technology, such as opting for a desktop or an HMD.

In VR, the spatial affordance is intended to be used as a simulator of reality, which means presenting a 3D world as we are used to. These features justify the usage of VR for an application on multiple ends, although not all of the content presented in VR is intended to be 3D. For instance, the user interface (UI) typically adopts a 2D format, adhering to familiar WIMP design standards [26]. These implementations generally take the form of a floating widget or window with which the user could interact using a pointer. The UI is commonly arranged as a plane, resembling its appearance on a flat display. Furthermore, data visualization in VR offers advantages like switching perspectives and promoting embodied cognition for novel data interpretation [40]. This flexibility fosters immersive experiences and facilitates precise insights into the data.

The dimensionality effects are crucial for different analyses. Goodstadt and Marti-Renom [20] discuss methods of displaying genomic interactions across dimensions: 1D genes and regulatory elements, 2D epigenetics influencing gene regulation, and 3D chromosomal spatial organization. They address challenges like diverse data types, uncertainty, dynamic time dependence, and integration. Halik and Kent [21] implemented an immersive virtual environment to explore urban topographic data, toggling between 3D and 2D representations of buildings. Their study found that participants preferred the 3D mode for familiarity and aesthetics but found the 2D mode more useful for practical purposes like orientation and wayfinding.

For entertainment, Tian et al. [67] investigated the effects of 2D and 3D VR video formats on emotional arousal using subjective and objective data. They compared macroscopic immersive VR (VR-2D), one of the primary techniques used in VR movies, and stereoscopic VR (VR-3D), obtained through professional stereoscopic VR cameras. Their findings suggest significant differences in brain activity between the two viewing modes. For geospatial data, Lochhead et al. [43] developed an immersive test to capture spatial abilities using an HMD. They designed a VR experience with 3D shapes and rotations, varying dimensionality (2D vs. 3D), and background complexity. Their results show significant differences in mental rotation test scores and times, highlighting the benefits of using immersive technologies for exploring 3D spatial data. These assessments prompt discussions on effective representations based on dimensionality that can benefit specific applications.

2.3 Desktop and HMDVR

Various research studies have demonstrated the benefits of using HMDVR over its desktop counterpart [5, 14]. Researchers have used HMDVR over desktop computers for different tasks and purposes, such as education in immersive environments [55], training in replicated settings [73], and entertainment [23]. The main difference lies in using stereoscopic displays such as HMDs and controllers instead of the traditional desktop setup (i.e., monitor, mouse, and keyboard). Several researchers have reported advantages in presence, engagement, and emotions [52, 63, 64, 67]. However, drawbacks such as cognitive load, motion sickness, and novelty effects have been encountered [31, 47, 48].

Researchers also aimed to demonstrate the feasibility of VR options for applications in different settings. For example, Checa et al. [7] aimed to validate the effectiveness of a VR game for teaching computer hardware assembly. They compared the VR game to a desktop version and a webcam instruction. Results showed that VR and desktop games increased student satisfaction compared to lectures. Students using the VR game had significantly better visual recognition skills and understanding of conceptual information, while the webcam group slightly outperformed in recalling factual information. Participants found the VR game easier to interact with than the desktop version.

Hombeck et al. [28] studied visualization techniques and performance differences between desktop and VR applications using a surgical application with 3D liver and vascular models. They found VR applications provided advantages in shape and distance estimation and temporal performance over desktops. Cao et al. [6] compared a driving simulation game in VR-HMD and desktop LCD, finding higher simulator sickness in VR-HMD and emphasizing the need for breaks to reduce discomfort. Johnson-Glenberg et al. [34] examined the immersion (PC vs. VR) and level of embodiment (low vs. high), showing that more active conditions improved content knowledge, but platform differences were not significant. These studies highlight how the choice of immersive medium affects application objectives, target populations, and potential benefits and drawbacks.

2.4 Research Questions

Considering the comparison between the immersion and dimensionality of the content, we aimed to evaluate how this aspect could affect participants' performance and user experience. For that, we planned to answer the following questions:

- **RQ1:** Do the immersion and dimensionality factors influence participant performance in charged particle simulation?
- **RQ2:** Do the immersion and dimensionality factors affect the reported task load on participants in charged particle simulation?
- **RQ3:** How do the immersion and dimensionality factors affect the participants' engagement in charged particle simulation?
- **RQ4:** Do the immersion and dimensionality factors influence the sensation of presence in charged particle simulation?
- **RQ5:** Do the immersion and dimensionality factors affect the system's usability in charged particle simulation?
- **RQ6:** Do the immersion and dimensionality factors affect the participants' skills in science lessons in charged particle simulation?
- **RQ7:** How do the immersion and dimensionality factors affect the participants' emotions in charged particle simulation?

2.5 Contributions

In this paper, we targeted to explore the utilized immersive degree (HMDVR vs. Desktop) and the dimensionality (2D vs. 3D) representation of the content for an interactive science simulation. The designed and developed application features a simulation of charged particle interactions and electric field lines. While extensive research has compared Desktop and VR applications, previous studies have primarily focused on platform differences, such as 2D flat screens versus stereoscopic views. In contrast, our work explores whether 2D or 3D graphics representation is more suitable for immersive simulations. Considering that VR might overwhelm users, we aim to investigate whether dimensionality could impact user performance and experience. In this paper, we reported the following contributions:

- a Desktop/VR application designed to simulate charged particle interactions,
- a comparison between the immersion and the dimensionality representation for simulations on Desktop/VR, and
- insights into preferred interactions when designing interactive simulations for VR applications.

In this study, we focused on charged particles due to their abstract nature and complexity for visualization in real-world settings, making them suitable for simulation. While our findings are specific to this topic, the design elements of our simulation—such as grabbing elements and changing simulation outputs—can be translated to other topics and scenarios that utilize these features. This suggests that the dimensionality and immersion in our simulation could potentially apply to and impact other science simulation topics.

3 MATERIALS AND METHODS

3.1 Participants

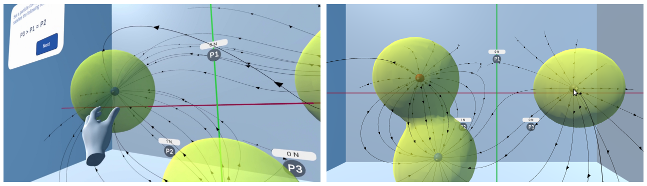
We conducted an *a priori* power analysis to determine the sample size for this study using G*Power v. 3.1 software [17]. For our four conditions (2 × 2 within-group study), a small effect size of $f = .25$ [8], and an $\alpha = .05$, to achieve an 80% power ($1-\beta$ error probability), our analysis recommended a minimum of 24 participants. We recruited 32 participants through emails sent to the students' listservs at our university and in-class announcements. Among the 32 participants (age: $M = 22.84$, $SD = 4.09$), 17 self-identified as males and 15 as females. Most of the participants considered having previous experience using VR (62.5%), and others reported having little (21.88%) or no (15.63%) experience with the technology. The participants volunteered to take part in this study. We did not offer monetary compensation to our participants.

3.2 Apparatus

3.2.1 Interactive Simulation

We developed our interactive charged particle simulation application (https://github.com/PedroAcevedo/2Dvs3D-Charged-Particle-VR-Simulation) in Unity (version 2021.3.30f1) game engine, using the features of the Oculus XR Plugin (3.3.0) (see Figure 2). Within the simulation, users can observe the exerted electric force and the effects of the electric field (EF) based on Coulomb's law and Faraday's principles, respectively.[1] We have incorporated the interaction between multiple charge sources, adhering to the superposition principle and the electrostatic assumption [42]. The elements used for the simulation were:

- cartesian axis representation,
- charged particles, represented as spheres with color codes (red for positive and blue for negative),
- electric field lines with arrows indicating the direction,
- interest points (IPs) that display the exerted electric force on a specific position, and
- an isosurface generated from the induced equipotential surface of the spheres.



(a) (b)

Figure 2: A participant interacts with the application (a) through an HMD and (b) using a desktop computer.

In terms of interactivity, users could adjust particle settings by rearranging available particles within the simulation area. They could move particles to any position within the delimited area. When a particle's position changes, all simulation elements are updated in real-time accordingly. This includes repositioning EF lines to target the new particle positions, recalculating exerted force on IPs based on updated distances (using Coulomb's equations), and adjusting the represented equipotential surface through mesh generation. If a particle moves outside the area, it is no longer considered in the internal calculations, subtracting it from the initial setting.

The virtual environment surrounding the simulation included instructions and UI elements to guide users through the application. To minimize distractions, users found themselves within an empty room, with the simulation positioned directly in front of them at their initial point of view (POV). While users could rotate in different directions, we have not included elements of interest outside the initial perspective.

3.2.2 HMD Version

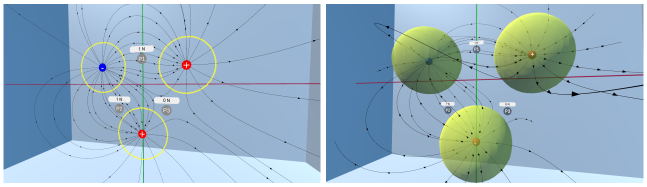
Our participants accessed the virtual environment via the provided HMD and interacted with the developed simulation using controllers (see Figure 2a). We tailored our application for the Meta Quest 2 HMD, utilizing Oculus toolkit prefabs to manage VR interactions like stereoscopic view, hands and head tracking, and object manipulation. In the virtual environment, participants embodied an avatar featuring only hands, rendered with a default white texture and semi-realistic features, including two gestures. These hand gestures became visible when participants activated the trigger or grab buttons on the controllers. We incorporated continuous movement as the locomotion method in the VR version of the application, although it may induce motion sickness in some users. However, our designed environment requires minimal movement, allowing participants to interact with the simulation without significant whole-body motion. We specifically targeted the VR application for seated use. In this version, our participants achieved the primary interaction with the simulation, moving a particle through grabbing action. For this action, the participant approached the particle, placed their virtual hand on the sphere, and pressed and held the grab button to adjust its position, creating a new simulation setting.

3.2.3 Desktop Version

Our participants accessed the virtual environment via a desktop computer and interacted with the developed simulation using a mouse and keyboard (see Figure 2b). We included a movable camera in the environment, enabling participants to adjust their perspective within the simulation. Upon entering the virtual environment, we placed our study participants with the simulation directly in front of them at a closer distance; they could move closer to the simulation using the WASD keys, which controlled movement along the x- and z-axes. Movement along the y-axis was limited, mirroring the constraints of the VR counterpart, where participants must stand to move along the y-axis. Additionally, participants could rotate the camera by pressing the right-click button on the mouse and moving the mouse in the desired direction. In this version, our study participants achieved the primary interaction with the simulation, moving a particle through drag-and-drop action. For this action, the participants positioned the mouse cursor over the sphere, pressed and held the left-click button on the mouse, and then moved the mouse to adjust the selected particle's position, creating a new simulation setting.

3.2.4 Dimensionality Differences

We presented the simulation in two different formats based on dimensionality, either in 2D or 3D mode (see Figure 3). We chose to represent the simulation differently based on dimensionality, using 3D primitives for the 3D mode and UI elements for the 2D mode. In the 3D mode, we included the z-axis in the simulation equations and calculations, enabling participants to place particles outside the $(0,0,0)$ plane. However, in the 2D mode, we restricted particle movement to the x- and y-axis. Additionally, the representation of calculated EF lines and equipotential surfaces is confined to the x- and y-axis in 2D mode, unlike 3D mode, which considers all z values in their calculations. For the surface, the marching cubes (3D) algorithm generated the mesh, while we employed the marching squares algorithm to outline the shape in 2D mode. Regarding the simulation elements, we presented the particles as spheres in 3D mode or as circular images in 2D mode, with their interaction based on their representation.



(a) (b)

Figure 3: We developed and evaluated charged particle simulations with (a) 2D and (b) 3D graphics.

Both dimensionality modes are placed in a 3D environment, providing users with a 360-degree view regardless of the mode. In the 2D mode, users face 2D content shown in a flat UI while still immersed in a 3D room. Additionally, the HMD's stereoscopic view introduces depth sensations to the experience. To maintain a sense

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[1] https://phet.colorado.edu/en/simulations/charges-and-fields

of presence in VR, we featured the 2D simulation within a 3D environment for both HMD and desktop versions, resulting in a 2.5D experience while still representing the simulation with 2D graphics.

3.2.5 Task

The interactive simulations offered various possibilities for activities surrounding the exploration of charged particle phenomena, but for this study, we narrowed it down to a specific task. Figure 4 illustrates the initial particle setting, comprising three charged particles and three IPs. We delimited the following instruction: *"Set a particle configuration that satisfies the following relation: P1 ($<$ or $>$ or $=$) P2 ($<$ or $>$ or $=$) P3."* We randomly defined the relation based on possible combinations of IPs and logical comparators ($<$, $>$, or $=$). Furthermore, we randomized the signs of the initial particle settings, and the same particle configuration (e.g., two positive and one negative or three negative particles) differed between task trials. With this instruction, we asked our participants to move the particle to find a particle setting that they consider to satisfy the relation between the displayed values of the IPs. The study participant should move the particle(s) they consider until they match the values and proceed. We instructed each participant to perform the task twice, with different particle settings and objective relations between the IPs.

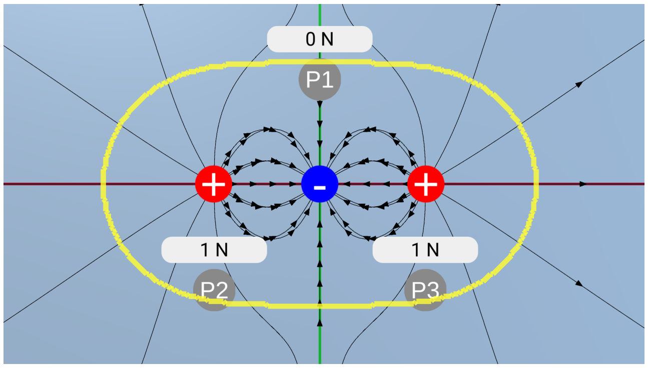

Figure 4: An example of a default particle setting. We placed the three particles on a line formation for the values in the IPs mismatch with the requested relation on the task. We instructed the participants to move them so they could set the IP values according to the requested relation.

3.3 Research Design

We employed a 2 (Immersion: Desktop vs. HMDVR) × 2 (Dimensionality: 2D vs. 3D) within-group design. We predefined the treatment order per participant using the Latin squares method [71] to eliminate carry-over (residual) effects across the examined conditions. For the study, we developed four experimental conditions to investigate how the immersion and dimensionality affected participants' user experience. Specifically, we examined the following four conditions:

- **Desktop and 2D representation (Desktop2D):** We presented the charged particle simulation using a 2D representation layout, and the participant interacted with it using a desktop computer.

- **Desktop and 3D representation (Desktop3D):** We presented the charged particle simulation using a 3D representation layout, and the participant interacted with it using a desktop computer.

- **HMDVR and 2D representation (HMD2D):** We presented the charged particle simulation using a 2D representation layout, and the participant interacted with it using an HMD and controllers.

- **HMDVR and 3D representation (HMD3D):** We presented the charged particle simulation using a 3D representation layout, and the participant interacted with it using an HMD and controllers.

3.4 Measurements and Ratings

3.4.1 Application Logs

We collected application logs to evaluate user interaction within the virtual environment. Specifically, we designed a module for capturing user performance data. The generated report includes completion time, reflecting the time users spent finishing the tasks when interacting with the simulation, as well as button clicks, indicating the buttons pressing frequency in either the controllers or mouse and distance moved, representing the total distance users traversed within the virtual environment. Additionally, the module records the latest IP values based on the delimited particle settings. This data collection begins each time a participant engages in the simulation, ensuring a fair comparison between experimental conditions.

3.4.2 Self-reported Ratings

We used self-reported measurements to address different user experience metrics. We employed several surveys to capture participants' responses. We use the NASA task load index (TLX) to capture the perceived workload [24, 25]. It comprises six sub-scales, such as mental demand and effort, to elucidate workload levels. The presence questionnaire [69] consists of a 6-item questionnaire that generates a single score to estimate how "present" the user felt in the virtual environment. For the participants' perceived usability of the experienced application, we used the system usability scale (SUS) [4]. This scale consists of ten items that allow us to compute a final usability score between 0-100. Additionally, we retrieved questions regarding engagement, emotion, and skill from the user experience in immersive environments questionnaire [66]. We adopted a 7-point Likert scale for all ratings. Responses ranged from 1 (strongly disagree) to 7 (strongly agree), or "not at all" to "very much" based on the question/statement.

3.5 Procedure

We provided a consent form, approved by our university's institutional review board (IRB), to students who volunteered to participate in the study. Once the participants signed the consent form, we proceeded with the following steps to start with the intervention. We asked the participants to fill in demographic data information such as age, gender, and VR experience. Before starting the study, the participants became familiar with the application; due to the degree of immersion, the application can be accessed using HMD or the desktop computer, so we created a tutorial scene for both mediums, showing the participants how to control the inputs and the simulation elements visuals, as prior research indicated that tutorial about VR controllers significantly improved performance and user experience [36]. In the introduction, we explained the controllers (how to move and look around), what a particle is, how the particle interacts with an IP, and the values of the exerted electric force. We delimited the exact instructions on the introduction for both devices. We randomized the order of the tutorials between participants. Then, the participants experienced four conditions using the application either through the HMD (Meta Quest 2 connected to Alienware PC Intel Core i7-8700k CPU, Intel UHD Graphics 630, and 32 GB of memory) or a desktop computer (same PC). After each experimental condition, the participants responded to a questionnaire including the reported self-perceived measures (see

Section 3.3). The participants were seated, wearing the provided HMD, or using a desktop computer to interact with the simulation. Immediately after the participants finalized the last questions, we asked them to provide comments or suggestions about the application. Finally, we thanked the participants and let them leave the lab.

4 RESULTS

We utilized a two-way repeated measures analysis of variance (ANOVA) to examine the collected data, incorporating immersion and dimensionality as our factors. We assessed normality through Q-Q plots of the residuals and conducted Shapiro-Wilk tests at the 5% level, confirming that the collected data met the normality criteria. We performed the statistical analyses using IBM's SPSS software version 25 and summarized the results in Table 1.

4.1 Application Logs

Completion Time (TIME). Our simple main effect analysis on the immersion factor (Wilk's $\Lambda = .743$, $F[1,31] = 10.721$, $p = .003$, $\eta_p^2 = .257$) showed that participants spent more time to complete the task when interacting with HMDVR ($M = 34.76$, $SE = 4.06$) than with Desktop ($M = 21.15$, $SE = 2.75$). However, we did not find a statistically significant result for the main effect of the dimensionality factor (Wilk's $\Lambda = .899$, $F[1,31] = 3.824$, $p = .072$, $\eta_p^2 = .101$) and for immersion × dimensionality interaction (Wilk's $\Lambda = .931$, $F[1,31] = 2.315$, $p = .138$, $\eta_p^2 = .069$).

Button Pressed (BTN). Our simple main effect analysis on the immersion factor (Wilk's $\Lambda = .508$, $F[1,31] = 30.050$, $p = .000$, $\eta_p^2 = .492$) showed that participants press buttons more times when interacting with HMDVR ($M = 9.09$, $SE = 1.01$) than with Desktop ($M = 4.27$, $SE = .51$). However, we did not find a statistically significant result for the main effect of the dimensionality factor (Wilk's $\Lambda = .894$, $F[1,31] = 3.668$, $p = .065$, $\eta_p^2 = .106$) and for the immersion × dimensionality interaction (Wilk's $\Lambda = .970$, $F[1,31] = .957$, $p = .336$, $\eta_p^2 = .030$).

Task responses (TR). We found no statistically significant main effect for the immersion factor (Wilk's $\Lambda = .997$, $F[1,31] = .088$, $p = .768$, $\eta_p^2 = .003$) for the dimensionality factor (Wilk's $\Lambda = .985$, $F[1,31] = .466$, $p = .500$, $\eta_p^2 = .015$), and for the immersion × dimensionality interaction (Wilk's $\Lambda = .997$, $F[1,31] = .088$, $p = .768$, $\eta_p^2 = .003$).

Movement (MOV). Our simple main effect analysis on the immersion factor (Wilk's $\Lambda = .839$, $F[1,31] = 5.946$, $p = .021$, $\eta_p^2 = .161$) revealed that participants move in the virtual environment more when interacting with HMDVR ($M = 42.11$, $SE = 4.31$) than with Desktop ($M = 30.22$, $SE = 3.73$). Furthermore, our simple main effect analysis on dimensionality (Wilk's $\Lambda = .528$, $F[1,31] = 27.670$, $p = .000$, $\eta_p^2 = .472$) showed that participants moved in the virtual environment more when we exposed them to the 3D representation ($M = 49.83$, $S = 4.97$) than to the 2D ($M = 22.50$, $SE = 3.05$). However, we did not find a statistically significant immersion × dimensionality interaction (Wilk's $\Lambda = .902$, $F[1,31] = 3.377$, $p = .076$, $\eta_p^2 = .098$).

4.2 Self-reported Ratings

Workload (TLX). Our simple main effect analysis on the immersion factor (Wilk's $\Lambda = .837$, $F[1,31] = 6.050$, $p = .020$, $\eta_p^2 = .163$) showed that participants rated their workload higher when interacting with HMDVR ($M = 2.72$, $SE = .09$) than with Desktop ($M = 2.46$, $SE = .07$). We did not find a statistically significant main effect for the dimensionality factor (Wilk's $\Lambda = .895$, $F[1,31] = 3.649$, $p = .065$, $\eta_p^2 = .105$). However, we found a statistically significant immersion × dimensionality interaction (Wilk's $\Lambda = .839$, $F[1,31] = 5.935$, $p = .021$, $\eta_p^2 = .161$), indicating that the 3D representation in the VRHMD condition made participant rate their workload higher.

Skill (SK). We found no statistically significant main effect for the immersion factor (Wilk's $\Lambda = .999$, $F[1,31] = .025$, $p = .875$, $\eta_p^2 = .001$), for the dimensionality factor (Wilk's $\Lambda = .964$, $F[1,31] = 1.171$, $p = .288$, $\eta_p^2 = .036$), and for the immersion × dimensionality interaction (Wilk's $\Lambda = 1.000$, $F[1,31] = .003$, $p = .955$, $\eta_p^2 = .000$).

Engagement (ENG). Our simple main effect analysis on the immersion factor (Wilk's $\Lambda = .524$, $F[1,31] = 28.112$, $p = .000$, $\eta_p^2 = .476$) showed that participants rated their perceived engagement higher when interacting with HMDVR ($M = 5.47$, $SE = .124$) than with Desktop ($M = 4.12$, $SE = .182$). However, we did not find a statistically significant result for the main effect of the dimensionality factor (Wilk's $\Lambda = .948$, $F[1,31] = 1.684$, $p = .204$, $\eta_p^2 = .020$) and for the immersion × dimensionality interaction (Wilk's $\Lambda = .993$, $F[1,31] = .224$, $p = .640$, $\eta_p^2 = .007$).

Emotion (EMO). Our simple main effect analysis on the immersion factor (Wilk's $\Lambda = .576.$, $F[1,31] = 22.840$, $p = .000$, $\eta_p^2 = .476$) showed that participants rated their emotions higher when interacting with HMDVR ($M = 3.88$, $SE = .098$) than with Desktop ($M = 3.28$, $SE = .091$). However, we did not find a statistically significant result for the main effect of the dimensionality factor (Wilk's $\Lambda = .980$, $F[1,31] = .623$, $p = .436$, $\eta_p^2 = .020$) and for the immersion × dimensionality interaction (Wilk's $\Lambda = .983$, $F[1,31] = .525$, $p = .474$, $\eta_p^2 = .017$).

Presence (PRE). Our simple main effect analysis on the immersion factor (Wilk's $\Lambda = .362$, $F[1,31] = 54.547$, $p = .000$, $\eta_p^2 = .638$) showed that participants rated their sense of being there higher when interacting with HMDVR ($M = 4.39$, $SE = 1.41$) than with Desktop ($M = 2.58$, $SE = .132$). However, we did not find a statistically significant result for the main effect of the dimensionality factor (Wilk's $\Lambda = .974$, $F[1,31] = .842$, $p = .366$, $\eta_p^2 = .026$) and for the immersion × dimensionality interaction (Wilk's $\Lambda = .989$, $F[1,31] = .336$, $p = .566$, $\eta_p^2 = .011$).

System Usability (SUS). We found no statistically significant main effect for the immersion factor (Wilk's $\Lambda = .956$, $F[1,31] = 1.141$, $p = .244$, $\eta_p^2 = .044$), for the dimensionality factor (Wilk's $\Lambda = .977$, $F[1,31] = .793$, $p = .397$, $\eta_p^2 = .023$), and for the immersion × dimensionality interaction (Wilk's $\Lambda = .995$, $F[1,31] = .160$, $p = .692$, $\eta_p^2 = .005$).

4.3 Qualitative Data

After the experiment, we asked our participants for their opinions about their experience with the developed VR application. Participants referred to the application mainly contrasting between the used mediums (HMDVR or Desktop). Overall, participants found the VR application to provide a "great" (P6), "cool" (P3 and P26), and "fun" (P10, P11, and P13) experience, with positive remarks mainly directed toward the HMDVR conditions. They found the HMDVR application to be "very engaging" (P3) and "intuitive" (P3 and P17). Indeed, the participants found the HMDVR application "easier to understand" (P12), "more fun" (P13), and "more useful to teach" (P22) than the Desktop counterpart. Some participants recognized the value of the HMD3D implementation, expressing their preferences in comments such as "loved the 3D VR" (P1) and "really like the color and tones of particles and force fields in the 3D conditions" (P8). Participant P19 highlighted HMD3D's relevance to education because 3D interactions are considered a "critical aspect of learning."

Table 1: Detailed results of our study (significant results are bold).

	TIME		BTN		TR		MOV		TLX		SK		ENG		EMO		PRE		SUS	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Desktop2D	19.73	13.97	3.48	1.78	92.19	22.39	2.39	28.07	2.48	.46	6.24	.80	4.03	1.34	3.30	.70	2.56	.96	87.24	11.53
Desktop3D	22.58	26.50	5.06	5.30	9.63	19.82	4.05	29.90	2.44	.46	6.10	1.00	4.20	1.43	3.27	.74	2.60	1.14	84.17	15.40
HMDVR 2D	26.42	17.67	7.42	3.50	93.75	21.06	24.60	18.04	2.51	.60	6.28	.80	5.26	1.36	3.79	.66	4.24	1.02	83.80	13.18
HMDVR 3D	43.10	43.18	1.77	1.86	9.63	23.55	59.62	38.60	2.92	.78	6.13	.80	5.68	1.13	3.97	.81	4.53	1.26	82.60	15.68
Main Effect (Immersion)																				
F	**1.721**		**3.050**		.088		**5.946**		**6.050**		.025		**28.112**		**22.840**		**54.547**		1.411	
p	**.003**		**.000**		.768		**.021**		**.020**		.875		**.000**		**.000**		**.000**		.244	
η_p^2	**.257**		**.492**		.003		**.161**		**.163**		.001		**.476**		**.424**		**.638**		.044	
Main Effect (Dimensionality)																				
F	3.482		3.668		.466		**27.670**		3.649		1.171		1.684		.623		.842		.739	
p	.072		.065		.500		**.000**		.065		.288		.204		.436		.366		.397	
η_p^2	.101		.106		.015		**.472**		.105		.036		.052		.020		.026		.023	
Interaction Effect (Immersion × Dimensionality)																				
F	2.315		.957		.088		3.377		**5.935**		.003		.224		.525		.336		.160	
p	.138		.336		.768		.076		**.021**		.955		.640		.474		.566		.692	
η_p^2	.069		.030		.003		.098		**.161**		.000		.007		.017		.011		.005	
Immersion $df = 1$, Dimensionality $df = 1$, Interaction $df = 1$, Error $df = 31$																				

Suggestions for improvement included enlarging the text size, with participants finding the numbers on the IPs "a little small" (P2) in HMDVR, and on the Desktop, "the numbers on the desktop could be larger" (P4). Participants criticized the keyboard-based movement feature on Desktop, suggesting alternatives such as "use scroll up or scroll down" (P12). Some participants felt that the Desktop made the application feel "more of an image" (P11), impacting the learning curve. Suggestions for new features included adding a "voice-over during text reading" (P8) and "adding haptic feedback to improve the realistic experience" (P29) in HMDVR conditions. Additionally, a participant (P8) suggested changing the pace of the task by including "extra tasks with just two particles" to target the cognitive demand of the activity.

5 DISCUSSION

Our conducted study highlighted several interesting findings. Regarding user performance (**RQ1**), participants took longer to complete tasks when interacting with HMDVR than in Desktop, regardless of dimensionality. We attribute the increased time to the more significant number of actions required in HMDVR conditions (e.g., button clicks and movement), likely due to participants' preference for the immersive experience HMDVR offers over traditional desktop interaction. Regarding our participants' actions, they moved and pressed more buttons when interacting with HMDVR than on the Desktop, implying a higher interest in interacting and performing actions in this environment. This result aligns with the novelty effect observed in VR experiences, where users may experience additional cognitive load due to unfamiliar interactions [31]. This effect may influence the duration of an HMDVR experience, which could last longer for novice users [50]. Although over 60% of our participants had prior VR experience and received introductory HMD training, the preference for VR features might have contributed to the extended task duration. This contradicts a previous study [70], where users perform faster through HMD than through a desktop interaction. In their experiment, they asked participants to teleoperate with an arm robot. Their results showed that their participants enjoyed VR and completed the task faster. However, in their study, the desktop (monitor) condition was significantly more cumbersome than the VR one. It is different from ours, where no significance is evident in usability.

For task load (**RQ2**), we found that participants considered HMDVR interaction more demanding than Desktop, as reported in previous studies [47, 64]. HMDVR requires mental effort, potentially affecting participant performance due to the learning curve associated with adapting to a new medium and navigating system actions. Moreover, task load increased notably in HMDVR conditions when content was presented in 3D, highlighting the impact of dimensionality. This suggests that understanding environments with 3D representations may demand specific spatial abilities from users [65]. The attentional influence of 3D elements aligns with findings by Barrett et al. [3], where VR with 3D features and 3D desktop conditions led to longer fixation durations, indicating prolonged examination of task features based on eye-tracking data. Such significant information processing demands could manifest in slower responses, as observed in this study regarding completion time.

HMDVR elicited greater engagement than Desktop conditions (**RQ3**). Previous studies indicate participants' preference for HMDVR regardless of content or task, emphasizing its immersive capabilities [12, 35]. However, some authors view this preference as a drawback, suggesting it may distract participants from task focus [52]. In contrast, in this study, participants achieved high task response scores, and we did not find significant differences between the mediums we examined. Regarding presence (**RQ4**), participants rated their presence in HMDVR conditions higher than Desktop, aligning with our expectations. HMD contributes significantly to a sense of presence by occluding surroundings and offering a 360-degree view of virtual worlds [62], a factor often cited as a primary reason for choosing VR [11, 55]. Assessing application usability (**RQ5**), participants deemed all conditions intuitive and easy to use, as evidenced by average scores surpassing expectations. Notably, the VR features implemented were considered intuitive, exceeding typical scores for immersive simulation-based environments [27]. Other studies have reported lower scores due to the inclusion of features on VR that cut off intuitiveness, such as complex instructions, tedious activities, or overwhelming features [29, 30, 68]. The intuitive nature of HMDVR conditions highlights continued VR technology usage and potential adoption for such experiences [19].

For the skill related to confidence in performing tasks with the application (**RQ6**), we did not find significant results. Lai et al. [41] found that HMD treatment has higher computer self-efficacy scores, even though no detailed analysis of their skill and only one of the instrument's questions was included. Our participants rated their emotions (**RQ7**) when interacting with the HMDVR experience as greater than when they were on the Desktop. Numerous studies have provided evidence that VR is an effective method for eliciting emotions [51, 63], often surpassing other display techniques like 2D images in emotional arousal responses [13]. Additionally, VR is noted for evoking positive emotions, indicating enjoyment, which could drive user engagement with such experiences [2]. These metrics, such as emotions and engagements, can be reflected in the participants' motivation during HMDVR experiences, enhancing effective learning or interaction, which strongly correlates with task success. Our findings extend the work of Halik and Kent [21] by showing the 3D mode preference when interacting with HMDVR; moreover, we highlight this preference against conventional Desktop for science simulations.

5.1 Practical Implications

When designing interactive science simulations, it is essential to show the outputs and the different variables behind the intended behavior. The complexity of the interaction should be reduced to focus the user on the simulation's output. According to this study's findings, we argue that Desktop is recommended if the rationale of the simulation is to focus the attention on the final output of the input setting due to a lower workload and completion time required for its interaction. However, if the user experience is a crucial factor for the application objectives, we have arguments to state that using VR with 3D representations could be meaningful to enhance user experience. The engaged nature could be exploited to promote the simulation as a learning content. However, in this study, where we presented the participant in an isolated and empty room with low features to avoid possible distractions, participants reported it higher in terms of workload, meaning that VR demands the participant a mental process that could be avoided using a regular desktop setting. Contrarily, dimensionality was found to be a not decisive factor in terms of the user experience, so either 2D or 3D representations could work, but based on some different averages and the user preferences, having the option to move the particles on the 3D dimensions, instead on a limited 2D plane was found meaningful.

5.2 Limitations

We would like to report some limitations of our study. These limitations do not invalidate the results but provide context for their interpretation and suggestions for future research. The UI placement was one of the issues during the interaction with the HMDVR environment, as users had to move from one part to another to follow instructions. We suggest placing the UI in a fixed position behind the simulation or on a wrist menu on the virtual hand for easy access. Moreover, participants' familiarity with the concept might have influenced their ratings, as they might not have completely understood how the simulation works. Although the scope of our study was not to teach the participants about charged particles and electromagnetism, we are unaware of whether their prior knowledge of the concept impacted their ratings. For future studies, we recommend collecting pre-test data on electromagnetism to determine the participants' understanding of the simulation's fundamentals before engaging and evaluating their experience.

Another limitation is that our designed simulation, while intended to be 2D, featured a 3D environment. This has potentially impacted user perception of spatial differences. Thus making the experience more accurately described as 2.5D. Additionally, the depth perception provided by the HMD's stereoscopic view limited the 2D representations. Future studies should explore ways to simplify VR scenarios. Moreover, in this project, we only focused on charged particles. Thus, we do not know if our findings apply to other science-related concepts; therefore, we cannot consider our findings as generalized. thus, we argue that further research is needed to explore whether our findings apply to different science fields.

6 CONCLUSIONS AND FUTURE WORK

We examined the effects of immersion and dimensionality when interacting with a science simulation. We found several results regarding the immersion mediums used and the influence of dimensionality. Our findings showed that the participants rated the HMDVR conditions higher regarding workload than the desktop one, as discussed in previous studies. Even for HMDVR conditions, we have reported higher engagement rates, emotions, and presence. These results reflect the participants' preference for being in a virtual environment through an HMD rather than a desktop computer. We found a significant interaction effect between immersion and dimensionality, showing that the HMD3D condition considered a higher workload; our participants preferred it according to their ratings and comments. We also highlighted the advantages of using VR experiences to enhance interactive simulations regarding engagement and presence for the participants versus the desktop counterpart. Utilizing 3D representations on HMDVR can increase those benefits. However, 2D/3D interactions on the desktop could also be adopted if the focus of the simulation interaction is surrounding the simulation output and analysis rather than providing an engaging experience for the user.

Future studies should include brief lessons and more detailed instructions to ensure participants initially understand the concept before interacting with the simulation. One limitation of our study is that we did not consider participants' prior knowledge during our recruitment process. We recommend future testing to include participants familiar with the assessed concept, as this can facilitate their interaction with the simulation and enhance their understanding of the outcomes. Further research could also explore differences between science simulations in immersive and non-immersive environments, particularly regarding spatial reasoning. Furthermore, future VR simulation evaluations could assess different interaction modalities, such as voice commands and task demands, including conceptual complexity and number of trials, on user experience and performance.

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