



## Article

# Virtual Reality in the Classroom: Transforming the Teaching of Electrical Circuits in the Digital Age

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**Abstract:** In response to the digital transformation in education, this study explores the efficacy of virtual reality (VR) video games in teaching direct current electrical circuits at a public university in Colombia. Using a mixed-method action research approach, this study aimed to design, implement, and evaluate a VR-based educational strategy to enhance undergraduate learning experiences. The methodology integrated VR into the curriculum, facilitating a comparison of this innovative approach with traditional teaching methods. The results indicate that the VR strategy significantly improved students' comprehension of electrical circuits and increased engagement, demonstrating the utility of immersive technologies in educational settings. Challenges such as the need for technological integration and curriculum adaptation were also identified. This study concludes that VR video games can effectively augment electrical engineering education, offering a model for incorporating advanced digital tools into higher education curricula. This approach aligns with ongoing trends in digital transformation, suggesting significant potential for broad applications across various educational contexts.

**Keywords:** electrical circuits; teaching; didactic strategy; virtual reality; emerging technologies; digital transformation; serious game



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## 1. Introduction

The integration of digital technologies within educational paradigms is revolutionizing traditional teaching methodologies, fostering more interactive and engaging learning experiences [1]. Among these innovations, Virtual Reality (VR) stands out due to its capacity to create immersive and realistic environments that engage students more effectively than traditional methods [2]. This study explores the use of VR as a dynamic interface between humans and machines within educational settings, specifically targeting the instruction of direct current electrical circuits across various educational levels [3].

Emerging technologies such as virtual reality have become a significant topic of contemporary academic discussion due to their valuable contributions to teaching and learning processes [4,5]. These technologies are emerging as innovative approaches that break away from classic teaching methods and offer active and engaging learning environments for students and professionals in the field of electricity [6,7]. Thus, the emerging technology that was explored in this study is virtual reality, which, from a theoretical perspective, is defined as a human-machine interface that allows users to experience an immersive environment through 3-dimensional graphic simulations aimed at entering the metaverse [8].

This technology provides a realistic interaction with the content [9]. In this sense, this study aimed to develop a didactic strategy based on virtual reality video games for teaching the fundamentals of direct current electrical circuits in secondary, technical, and higher education. These tools are increasingly used to prevent electrical accidents, such as those occurring in substation control [10].

Virtual reality offers an interactive platform that significantly enhances the comprehension of complex scientific concepts through three-dimensional simulations. This immersive experience not only improves understanding but also increases student motivation and engagement, thereby making the learning process more appealing and effective. Despite initial barriers such as high costs and limited technological accessibility, recent advancements have rendered VR tools more accessible, spurring renewed interest and expanded research into their potential educational benefits [11,12].

The transformative impact of VR extends beyond mere visualization; it changes pedagogical approaches in science and technology education [13]. By enabling students to interact with virtual objects, VR facilitates a hands-on approach that is particularly advantageous in fields such as electrical engineering, where theoretical concepts can be abstract and difficult to grasp [14,15]. Research indicates that VR can significantly reduce cognitive load, providing a more intuitive understanding of complex theories [16,17].

Moreover, the inclusion of VR in educational settings enhances inclusivity and accessibility, catering to diverse learning needs and styles [18]. Studies have shown that VR's multisensory, immersive environments are particularly beneficial for students with learning disabilities, helping them engage with content in ways that are often unachievable through conventional methods [19,20].

Recent studies underscore VR's expanding role across various disciplines. For instance, Vergara et al. [21] demonstrated how VR platforms could simulate complex engineering tests like concrete compression, enhancing student familiarity with potentially hazardous equipment in a risk-free environment. Furthermore, Vergara-Rodríguez et al. [22] utilized VR for training in ultrasonic non-destructive testing, showing that VR not only reduces training costs but also prevents the risks associated with handling real equipment. These applications highlight VR's potential to transcend traditional educational boundaries, offering a versatile tool for both theoretical and practical instruction.

As VR technologies continue to evolve, their adaptability and scalability suggest that they could become foundational in educational systems globally, reshaping how educational content is delivered and experienced across various levels and disciplines. The empirical evaluation of this VR teaching strategy included both quantitative and qualitative assessments to determine its impact on learning effectiveness, usability, and student engagement. Findings suggest that VR significantly enhances educational experiences by providing interactive and engaging environments that support complex cognitive tasks such as understanding electrical circuits [23,24].

This research was conducted in collaboration with the Research and Development Group in Electromechanical Systems (GRIDSEs) and Research in Science, Education, and Technology (RESET) at the Pedagogical and Technological University of Colombia. It employs VR video games to teach the fundamentals of electrical circuits, integrating action research methodologies to ensure practical relevance and effectiveness. The initial phase involved a review of existing didactic strategies, followed by the development and implementation of a VR solution tailored to enhance learning outcomes in electrical circuit education. Thus, this study not only highlights the effectiveness of VR in enhancing electrical circuit education but also illustrates its potential as a transformative educational tool. The findings advocate for the integration of VR technologies in curriculum design, addressing the evolving demands of digital literacy in higher education [25,26].

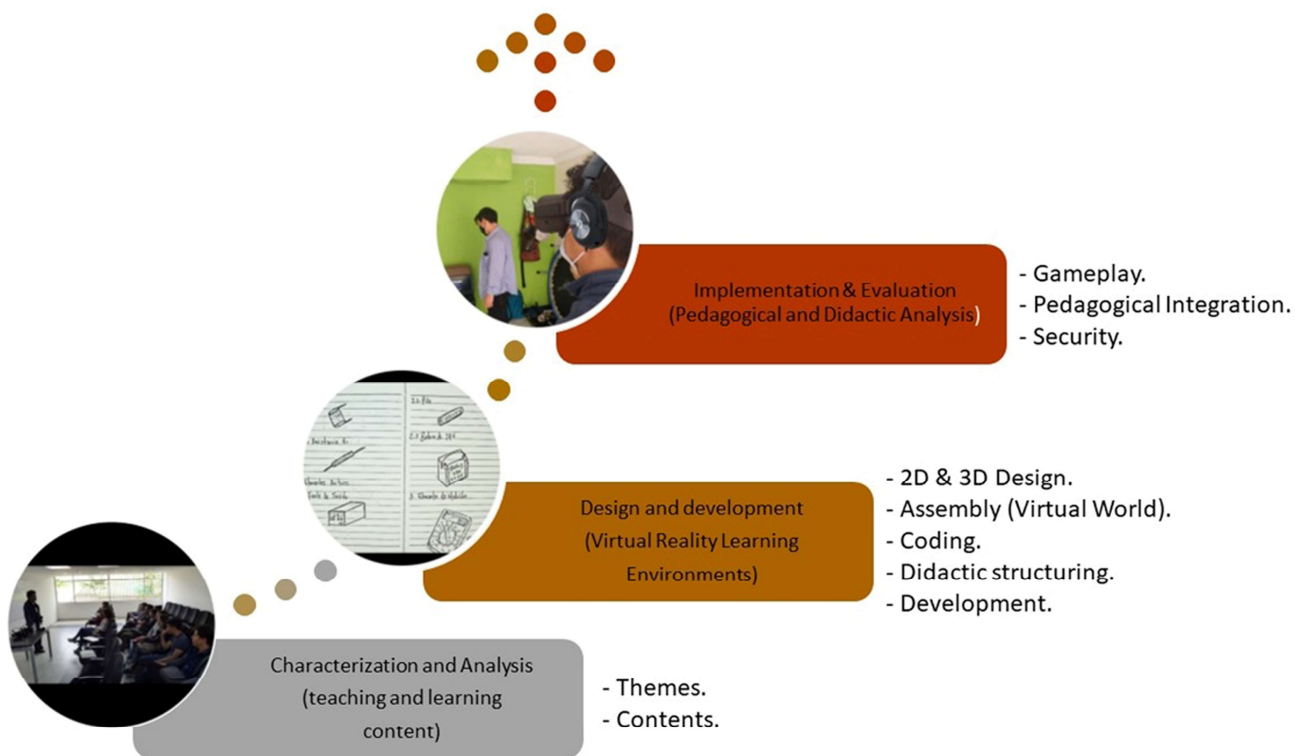
## 2. Methodology

The methodological approach of this study was undertaken using a mixed method, supported by action research following Lewin's postulates, where the entire research

proposal was structured into four stages: plan, act, observe, and reflect. Creswell [27] states that this type of research “is similar to mixed research methods as it utilizes a collection of quantitative, qualitative, or both types of data. However, it differs from these by focusing on solving a specific and practical problem” (p. 577). Notably, action research was first promulgated in 1944, envisioned as a research method with an experimental approach in social sciences, prioritizing action on social issues [28].

Currently, this method is widely utilized in the field of education, offering possibilities for intervention in communities with local problems that pave the way for transformation and reflection [29,30]. It also allows researchers to theorize about praxis and self-reflect on their teaching practices [31,32]. In action research, the researcher identifies a problem related to action, employing various instruments to define the topic of interest and diagnose significant weaknesses along with supporting theories, aiming to improve educational practices. This approach can be conducted individually or in teams [33].

During the planning phase, the need to incorporate an instructional design model was identified to plan the entire teaching strategy based on virtual reality effectively. To this end, the ADDIE model was employed, which involves structuring the sequence of content creation—didactic and interactive—based on five criteria: analysis, design, development, implementation, and evaluation. Muñoz and González [34] suggest that these steps can be followed sequentially or simultaneously to design teaching materials, as summarized in the diagram below (Figure 1).



**Figure 1.** Methodological development diagram.

The virtual reality environment was developed using the Oculus Quest tool. This platform enables users to interact in real-time with a simulated three-dimensional environment via multiple sensory channels, emphasizing its main features such as visual and spatial representation, immersion, and 3D sound. These attributes are crucial for fostering the development of educational and interactive content.

The initial phases of this study involved a diagnostic analysis of the VR tool with students from the technology degree program enrolled in the “Fundamentals of Electrical Circuits” course. This cohort consisted of ten students, including two who were repeating the course, that were selected to explore their comprehension and challenges related to the

topics of symbology, measurement, and circuit types in a controlled, virtual environment. To ensure a comprehensive evaluation, a supplementary assessment was conducted with an additional 17 students, bringing the total number of student evaluators to 27. This broader group allowed for a robust assessment of the VR system’s usability, pedagogical integration, and safety in a wider educational context. Additionally, an evaluation panel comprising five experts in educational technology and electrical engineering was included to provide expert perspectives, ensuring the results reflect practical usability and pedagogical efficacy. The evaluation employed a Likert scale survey [35] to gather detailed and nuanced feedback, ensuring thorough vetting from both usability and educational perspectives. The survey used for this evaluation can be found in Supplementary Materials File S1.

To address potential risks associated with the use of virtual reality (VR) environments, such as falls, dizziness, and other symptoms [36], several precautionary measures were implemented. Prior to participation, all students were fully informed about the nature of this study and the potential risks involved. Informed consent forms were completed by each participant, ensuring that they were aware of the scope and responsibility entailed in the evaluation phase of the immersive VR resource developed.

To supplement our findings and mitigate the impact of having a smaller initial cohort, we established a second population comprising a panel of five experts with extensive experience in the electrical sector and educational gamification. This panel, detailed in Table 1, was meticulously selected based on rigorous inclusion criteria, primarily their professional experience exceeding ten years in relevant fields. The experts evaluated and analyzed the usability characteristics, pedagogical integration, safety measures, and the overall behavior of the virtual reality laboratory in teaching basic electrical circuits. Their insights were crucial for validating the effectiveness and educational value of the VR environment under conditions simulating real-life usage. This dual approach, combining both student interactions and expert evaluations, provided a comprehensive analysis of the VR application, ensuring robust testing and feedback that aligns with the high standards required for educational innovations in technical disciplines.

**Table 1.** Expert panel composition and qualifications.

Panel of Experts	Profession	Professional Experience	Virtual Reality Experience	Supervised Subjects
1	Electronic engineer, Master of Computer Science, and Ph.D. in engineering	18.3 years	No	Electrical circuits, electric drives, analog electronics, digital electronics, and power electronics
2	Industrial designer—with teaching experience in the area of 2D and 3D design	15.7 years	Yes, thesis supervision in gamification.	Basic and secondary education technology
3	Electromechanical engineer and Specialist of Industrial Automation and Master of Industrial Automation	28.4 years	No	Electrical circuits, electric drives, analog electronics, digital electronics, and power electronics
4	Electrical engineer, Master of Engineering with an emphasis in electrical engineering	20.2 years	No	DC electrical circuits
5	Graduate of Industrial Education, Master of E-learning, Ph.D. in creation	26 years	Yes, direction and chair of the postgraduate projects in gamification.	Educational digital ecosystems and educational innovation and information communication technology

The following description outlines the methodology used in this study, including details on the sample population, the various research methods applied at different stages,

and the specific tools employed to evaluate the impact of virtual reality (VR) on students’ learning experiences.

2.1. Methodological Process

2.1.1. Qualitative Methodology

Qualitative assessments were conducted at multiple stages to gather nuanced feedback on the VR environment. These included structured interviews and observational studies, which provided critical insights into the usability and educational value of the VR settings.

2.1.2. Quantitative Methodology

Quantitative data collection began with a baseline evaluation of students’ understanding of key concepts in electrical circuits. This phase employed a structured questionnaire to identify initial knowledge gaps and measure learning outcomes post-intervention.

2.1.3. Measurement Tools

To rigorously assess the effectiveness of the VR application, a customized questionnaire was developed based on Olsen’s frameworks for serious games’ usability testing. The immersive quality of the VR experience was enhanced using Oculus Quest technology, which supports interactive learning through six degrees of freedom, ensuring a highly engaging and educational experience. Each session was carefully timed to last no more than thirty minutes to optimize focus and prevent cognitive overload.

3. Results

3.1. Initial Diagnosis

An assessment was conducted with ten students enrolled in the “Fundamentals of Electrical Circuits” course. The objective was to gauge their level of knowledge on key concepts. This assessment covered various topics, including symbols, electrical components and units, areas of measurement, series circuits, and mixed circuits (Table 2). Each question was categorized by theme and meticulously analyzed. This process enabled the identification of the students’ strengths and weaknesses concerning their knowledge base.

Table 2. Knowledge level test responses.

Ask	Symbology (1a)	Units (1b)	Measurement Zones (2)	Series Circuit (3)	Mixed Circuit (4)
Correct answer	3	9	1	3	4
Wrong answer	7	1	9	7	6

The analysis of the preliminary data, as illustrated in the preceding table, reveals significant gaps in knowledge across most of the evaluated topics. This initial diagnostic exercise proved to be the most critical input for determining the specific subjects to be addressed within the teaching strategy, which was operationalized through the virtual reality laboratory. The analysis indicates that 90% of the students can identify and associate electrical components with their corresponding units. However, a majority struggles with other areas, including symbols, measurement domains, series circuits, and mixed circuits.

3.2. Design and Development of Virtual Reality Modules

For the design and development of the video game, two versions of the teaching strategy were developed, leveraging challenge-based learning to foster critical thinking, creativity, and curiosity among students. This approach facilitates a deeper understanding of the subject matter and enhances problem-solving skills, as supported by Romero-Yesa et al. [37] and Kaya and Ercag [38], who have documented the effectiveness of challenge-based learning in stimulating significant educational engagement and improvement in learning outcomes. A preliminary knowledge diagnosis was performed to identify the most challenging topics for

students, which then informed the thematic content incorporated into the video game. The chosen topics were meticulously aligned with the course syllabus to ensure relevance and educational integrity.

Further detailing the video game’s design, we incorporated instructional elements, interface designs, and safety measures tailored to the educational context. Notably, the gameplay was structured to include specific time allocations for each challenge, detailed in Table 3 below, ensuring that each session maintained optimal engagement without overwhelming the students. The sequence of scenes, evaluations, and feedback strategies were carefully orchestrated to provide both auditory and visual cues, enhancing the immersive experience while safeguarding the educational objectives. The sound environment and other design elements were chosen to minimize distractions and maximize learning efficacy, with the entire design process reflecting a meticulous approach to integrating educational technology effectively.

**Table 3.** Requirements for the design and development of the video game.

Requirements	Justification	Alternative
Characterization of the themes	To stop the design and development of the modules, the themes that represented the greatest difficulty in the contextualization of knowledge were taken into account.	The topics were selected based on the subject’s curriculum and the application of the knowledge level test.
Virtual reality	Virtual reality was used due to its great benefits in terms of didactics and pedagogy, since significant learning has been demonstrated.	The total immersion of the user within the video game allows for a pedagogical and didactic connection.
Safety	Prevents the user (player) from suffering physical injuries. It is recommended to perform active pause practices every 15 min for a period of 30 min to use the virtual reality glasses again.	The Oculus Quest virtual reality device was used, due to its safety guardian system, which avoids collisions with the real world.
Gameplay	The video game was developed under a criterion of rules and conditions—Game Core, Game Engine, Game Interface—facilitating the response interaction between the user and machine.	<p>Game Core: use of an interactive character that narrates and introduces the video game.</p> <p>The following system of rules was defined: The accumulation of points. This is an individual video game. Challenges only have one solution. There is a time limit for each challenge.</p> <p>If the player, at the end of each module, does not solve the challenge correctly, he must return to the beginning of it. If the player solves the challenge correctly in one module, he or she will automatically continue to the next.</p> <p>Game Engine: The 3D objects were designed under gravity parameters and high-quality rendering, obtaining a realistic appearance of the materials associated with each electrical element. Oculus Touch controls were used for the communication system. A VR display device, Oculus Quest, was used.</p> <p>Game Interface: Auditory feedback means (narrative audios, button sounds, and auditory timers) and visual feedback (images, colors, shapes, numbers, symbols, letters, and three-dimensional objects) were used.</p>
Graphic section	The aim is for the content to be realistic and to have a high resolution, omitting distracting agents, and for the player to be the one who intuitively discovers the video game, within the user interface.	Naturalness in movements, quick interaction responses in real time, realistic renderings, and scales according to the real elements.
Music and sounds	During the experience, the user will need to be oriented and guided in each thematic module and have feedback on the practices.	Through narration and sound effects, the video game will be comfortable and intuitive to use.

Table 3. Cont.

Requirements	Justification	Alternative
Duration	Within each interaction, the user will have a time limit to be able to correctly solve the modules.	The video game will have a pop-up message in the last 10 s of each interaction.
Theme contextualization	The context of the video game and all the elements of the scenario are related to the topic of fundamentals of direct current electrical circuits.	The scenario was designed, simulating an electricity laboratory, ruling out any distraction within the practical experience.
Quantitative measurement of learning	As this is a video game focused on teaching, it is important to evaluate the results in each thematic module.	A scoring system was designed that allows for the measuring of the results by modules and additionally establishes a final sum of the victory of the video game.
Didactic environment	Electrical concepts, being ambiguous and intangible, become more difficult to understand and contextualize.	The scenario has the objects associated with a symbol and a type of electrical element.
Degrees of freedom	The controls and interface with the use of Oculus Quest offer six degrees of freedom, allowing free and natural movements in space.	At the time of immersion, the user has the option to move in all three axes and perform head rotations using the Oculus Quest devices.

### 3.3. Conceptual Modeling

In this phase, initial concepts for the video game were sketched by hand before being digitized. Figure 2 illustrates an initial layout of the game environment, detailing the quantities of electrical components utilized and establishing both the chronological sequence and the mechanics of the game, including the setting, immersion, interaction, and puzzles.

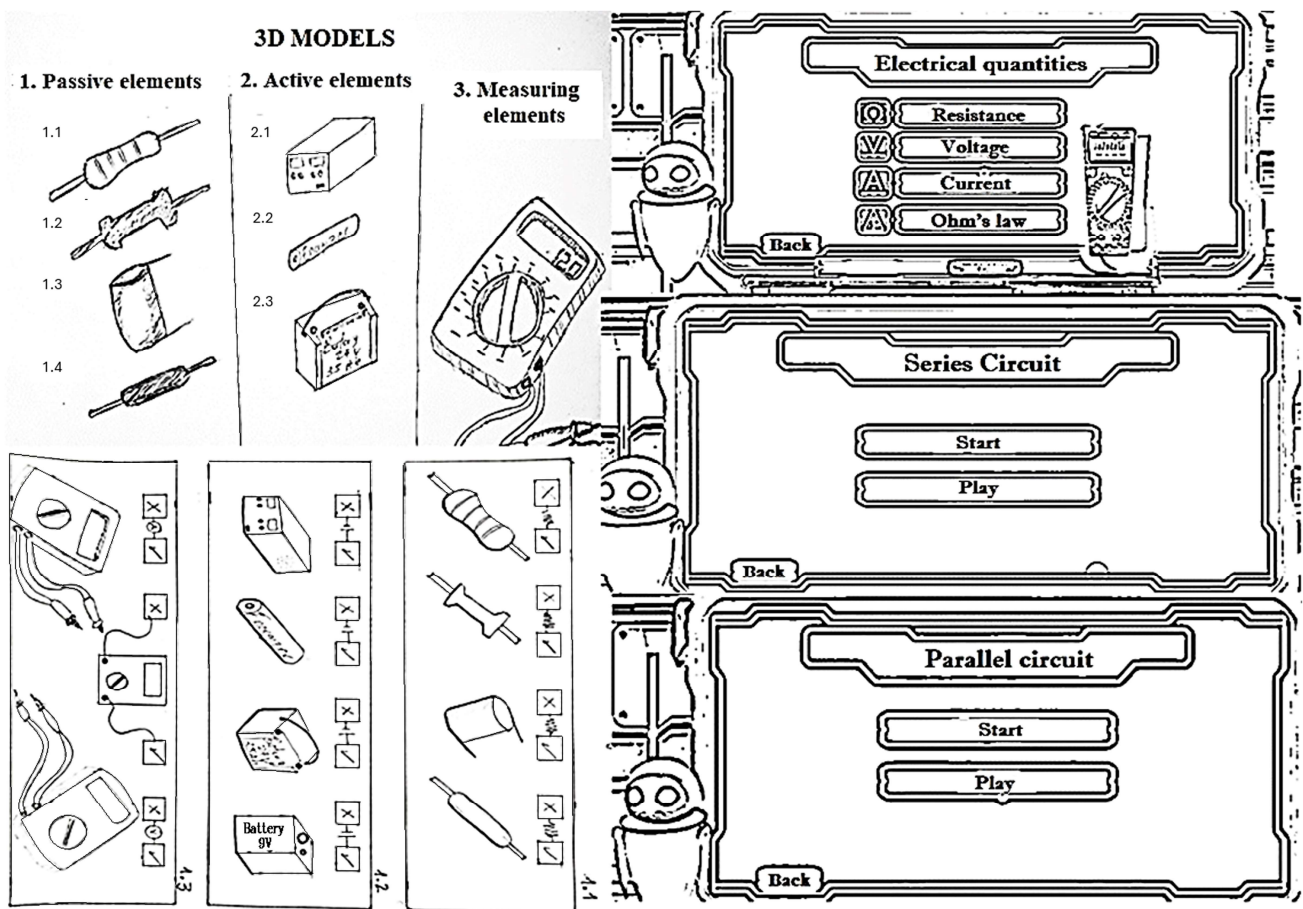


Figure 2. Spatial distribution of the module.

### 3.4. Production of Artistic Resources

During this stage, various artistic assets were created, including objects, textures, videos, illustrations, and audio narratives. The following tools were employed for their development: Blender was used for modeling three-dimensional objects in .blend format; Corel Draw was utilized for editing and creating vectors, specifically Sprites, in .png format; and Audacity was used for editing and creating narrative audio files in .mp3 format. For the rendering phase, a laptop equipped with an Intel Core I7 processor, 16 GB RAM (Intel Corporation, Santa Clara, CA, USA), and an NVIDIA GEFORCE RTX 2060 (NVIDIA Corporation, Santa Clara, CA, USA) graphics card was used.

### 3.5. 3D Modeling

The electrical objects were modeled in three dimensions with a high level of detail, coupled with the assignment of materials, which were rendered by the Cycles engine to achieve a realistic representation, as observed in Figure 3. The design of all objects within the learning environment utilized polygonal modeling techniques, favored for their ability to create complex shapes through the manipulation of vertices, edges, and faces. The primary tools employed in this process were Extrude and Subdivision, which are staple features of modeling software, particularly Blender in this instance. These tools enable the addition of intricate details to the mesh by starting with a basic geometric shape in edit mode and then selecting specific faces to extrude. The figure below displays examples of the modeled objects. The development of virtual reality equipment has led to significant advancements, particularly in the evolution from virtual reality helmets to virtual reality glasses. These glasses have enhanced scenario resolution, portability, and software development, including platforms like Unreal Engine™ and Unity™ © [39].



Figure 3. Element modeling.

#### 3.5.1. Vectorized—Graphical User Interface

For the creation of buttons and electrical symbols, initial sketches were refined and subsequently vectorized using the Corel Draw program, specifically its free version. This approach facilitated the production of high-resolution vectors in .png format, ensuring that the graphical elements retained clarity and detail suitable for the educational content (Figure 4). The graph below displays the vectors and Sprites that were pre-designed and

edited in .CDR format, sourced under a free license from the OpenGameArt repository, showcasing the variety and quality of these graphical components. Similarly, 2D elements play a crucial role in student tasks, as traditional methods utilize graphics and symbols that help connect concepts with student understanding [40].



**Figure 4.** Vectorized graphic elements.

As illustrated in the previous graph, symbols served as reference images to signify the type of electrical element each represented. Moreover, vectors were utilized to graphically underscore the concepts covered in each module, and a logo was crafted to encapsulate the essence of the game, serving as a key part of the virtual reality learning environment's identity.

The process for vectorizing images began with the initial sketching of buttons and symbols, followed by their vectorization in Corel Draw (X9). Subsequently, the hierarchy of the vectors was organized in terms of frames, titles, subtitles, and buttons. These vectors were then exported in .png format to the Unity3D engine. The final steps involved converting the .png vectors into 2D sprites and arranging the spatial distribution of buttons within the input menus.

### 3.5.2. Construction of the Scenario

For the construction of the setting, a 3D digitization was arranged, creating a futuristic electricity laboratory. This environment comprises three-dimensional elements including an instruction and menu screen, a workbench, and various 3D objects. The design draws inspiration from a futuristic laboratory theme, sourced from Unity's Asset Store. As depicted in Figure 5, the aim is to foster a gaming and immersive experience for the user. This immersion is further enhanced through visualization with virtual reality devices, such as Oculus Quest, thereby stimulating motivation during the execution of learning activities.

For the final arrangement of the scenario, the 3D objects were exported in .blend, .obj, and .fbx formats to the Unity video game engine. This step facilitated their integration within the scenario and its associated themes. Following this integration into Unity®, with the 3D elements designed by the authors, the appropriate lighting for the 3D environment was established. This meticulous process culminated in the creation of the environment depicted in Figure 6 as the result.

To ensure students' effective engagement and understanding, initial instructions are provided through 2D mediations such as texts and images. These instructions are presented on a monitor within the VR environment, explaining, in detail, the steps and tasks students need to perform. This preparatory phase helps students comprehend their roles and the activities involved in the immersive learning environment. Following this, students interact with the 3D resources and activities designed to achieve learning outcomes related to electrical circuits. The preliminary instructions are delivered via a computer, a familiar resource in the computer laboratories of the educational institution, facilitating a smooth transition to the immersive 3D experience. This method leverages both 2D and 3D elements, creating a comprehensive learning pathway that enhances educational outcomes. Figure 7a,b illustrate the interaction within the serious game. In the selection activities,

students use controls to pick up 3D objects and place them in the correct category of circuit elements, as shown in Figure 7a. In the circuit-construction phase, students select elements such as sources, resistors, and conductors to assemble a series circuit on a giant breadboard within the 3D virtual environment, as depicted in Figure 7b. This structured integration of 2D and 3D instructions and activities ensures a progressive and engaging learning experience.



Figure 5. Scenario design in post-processing mode.



Figure 6. The Virtual Electrical Lab—the VE Lab.



**Figure 7.** (a) Interaction with 3D objects for categorizing circuit elements. (b) Construction of a series circuit on a giant breadboard in the 3D virtual environment.

The graphical user interface (GUI) of the virtual laboratory features various menus that offer students the opportunity to temporarily register their names before proceeding with the different modules available in the learning environment. Additionally, an instruction menu provides guidance on using the controls to interact with 3D objects and integrate them into the construction of electrical circuits. Furthermore, the explanatory interface plays a crucial role in contextualizing the material through images, illustrations, and text, elucidating the electrical concepts and virtual reality principles necessary for engaging with the virtual world effectively.

In response to the innovative application of VR environments to simulate traditional educational tools like monitors displaying circuit diagrams, the well-documented educational benefits of serious games and digital game-based learning environments are harnessed. Studies by Protosaltis et al. [41] and Anastasiadis et al. [42] illustrate how these digital platforms catalyze learning by enhancing student engagement through interactive and immersive experiences. Digital games, especially those designed for educational purposes, transform traditional learning landscapes into comprehensive and interactive environments where students actively participate and engage with content. This interactive modality, preferred by digital natives or modern learners who thrive in digital-rich settings, promotes a deeper understanding and retention of complex concepts such as those encoun-

tered in electrical circuits. The virtual display of a monitor in the VR laboratory serves more than a mere visual replication; it integrates with interactive elements that allow students to manipulate and experiment with circuits in ways traditional static displays cannot match. By incorporating serious games into education, the natural curiosity and engagement of learners are leveraged, transforming their interaction with content from passive reception to active involvement—a crucial shift in technical education where practical understanding and the application of knowledge are key. Moreover, the inclusion of game elements, such as points, levels, and feedback, not only makes the learning process more engaging but also aligns with pedagogical strategies that enhance motivation and improve learning outcomes. Embedding traditional educational content within a VR platform adheres to modern educational theories and provides a pedagogically enriched environment that is adaptive, interactive, and reflective of how students best learn today, aligning with the advantages of serious games in education which include improved cognitive gains, higher motivation and engagement levels, and enhanced problem-solving skills.

### 3.6. Logical Structuring of the GUI

Figures S1 and S2 (in the Supplementary Materials) showcase the class diagram (logical structure) of the GUI, detailing the various methods, variables, and plugins that facilitate user interaction. This diagram serves as the foundation for all user navigations within the GUI, enabling seamless interactions with menus, activities, and conceptual frameworks. In other research, interaction is crucial for familiarizing users with levels and tutorials to help them achieve each objective [43].

Figure S1 presents a concept map illustrating the relationship between the user interface and game controls within the virtual reality environment. The GUI is divided into two key elements: the “VR Instructions Menu” and the “Main Menu”. This map highlights how the user interacts with the controls and various menus, showcasing the different activities involved in the application’s use for teaching circuits. Figure S2 illustrates the interaction and components within the virtual world designed to teach concepts of electrical symbology, such as electrical resistance, voltage, and electrical current. The controls and gameplay modules are configured to allow for the selection and manipulation of various circuit elements, enabling users to identify passive, active, and measurement components. Additionally, users can engage in several questionnaire challenges where they must select the correct answers. Upon completing the questionnaire, users can build a circuit on a protoboard using different virtualized elements, enhancing their ability to manipulate and construct circuits.

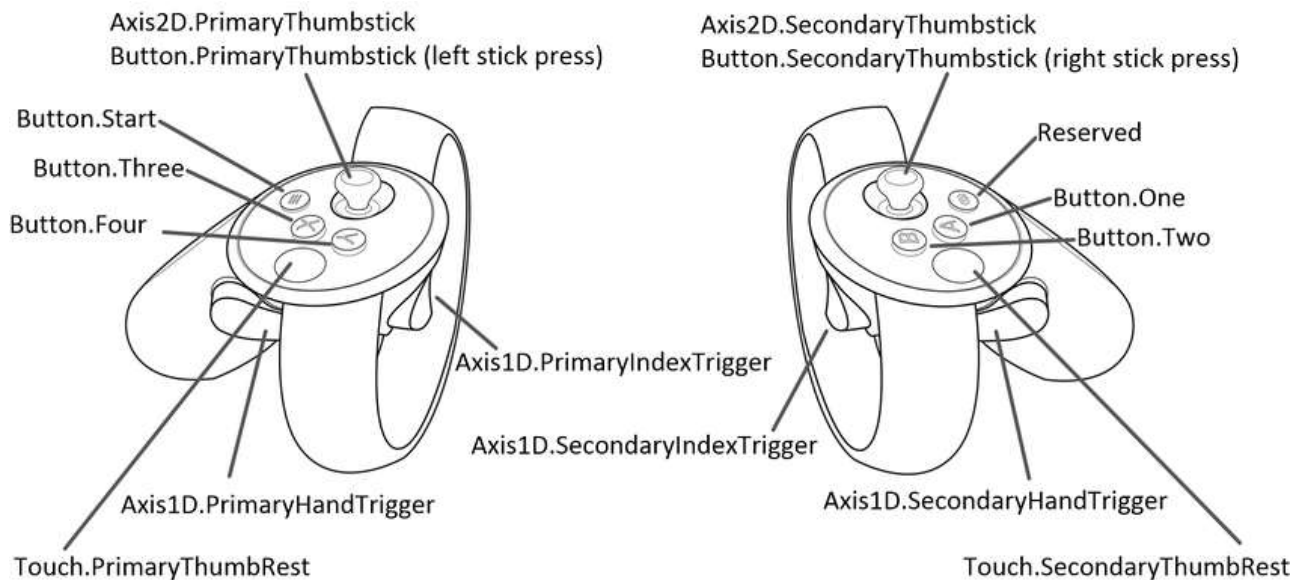
The educational structure of the video game is divided into two main sections: the first part delivers theoretical content, introducing concepts through narratives and texts. The second part engages students with interactive puzzles, allowing them to apply the concepts they have learned. This dynamic approach is enhanced by the inclusion of a scoring system, timers, sounds, and pop-up messages, which provide feedback and signal achievement to the students.

### 3.7. Graphical User Interface Coding and Programming

The programming behind the graphical user interface (GUI) was executed in the C# (C Sharp) programming language, utilizing the Visual Studio 2019 Integrated Development Environment (IDE) and integrating it into the Unity video game engine. The development process involved coding various scripts related to entry, GUI navigation, instructions, question-and-answer interactions, final results, and circuit creation. These scripts underpin the interactions within each module of the virtual learning environment, facilitating a seamless and interactive educational experience.

### 3.7.1. Control Programming

Control programming was specifically designed to enable interaction with the input and grip buttons, allowing for the selection and manipulation of objects within the virtual space. Figure 8 illustrates the control mechanisms.



**Figure 8.** Oculus Touch input system in Unity. Source: Unity Manual [44].

The controller controls utilized were Oculus Touch, and the final coding was implemented within the Unity3D video game engine, version 2019. It was essential to identify the input buttons of the Oculus Touch controller within the Unity3D engine and utilize its native Oculus package, named Oculus Integration. This package comprises basic Oculus VR features, components, scripts, and plugins in Unity, facilitating certain user actions.

### 3.7.2. Generation and Installation of the Apk on the Oculus Quest Device

The final compilation of the virtual reality environment and the generation of the APK were conducted using Unity. Subsequently, the Oculus Quest device was connected, and the application was installed via the command prompt using the respective commands.

### 3.8. Implementation and Evaluation of the VR Teaching Strategy

A panel of five experts was selected to use and analyze the teaching strategy, named the Virtual Electrical Lab. This process allowed for the compilation of observations through a questionnaire to establish criteria for improvements. The observations, recommendations, and identified limitations aimed to enhance the video game in terms of usability, pedagogical integration, and safety.

At the start of the session, with each expert in the virtual reality laboratory, instructions for using the Oculus Quest virtual reality display device were provided, along with an introduction to the virtual learning environment. The progress within this environment was observable from outside the VR device via a screen.

In refining the assessment tools for the serious game, the necessity to adapt the evaluation strategy to better suit the developmental stage of the project was recognized. Initially guided by general frameworks from the literature [45], a comprehensive questionnaire was specifically designed to address usability, pedagogical integration, and safety aspects, drawing from established methodologies in usability testing for serious games. This approach ensures that the game not only meets technical standards but also aligns with educational goals, providing a safe and effective learning environment. The results from this structured evaluation are instrumental in directing ongoing adjustments and enhancements, confirm-

ing the game’s readiness for eventual academic applications and highlighting its potential for broader educational impacts.

Usability and interaction (expert panel): The survey results from the results on usability (Table 4) indicate a highly positive reception of the VR tool’s instructional quality and design features. Preliminary instructions provided by the developer or course instructor were rated as either “Excellent” (60%) or “Very Good” (40%), with no responses falling into lower categories. Similarly, the quality of in-game instructions for controls, object handling, and circuit building received the same high ratings, indicating clear and effective guidance for users. Satisfaction with the 3D environment design, including colors, textures, audio, voices, 3D objects, lighting, and scales, also scored highly, with 60% rating it as “Excellent” and 40% as “Very Good”. This reflects the immersive and visually appealing nature of the VR environment. The 2D interface design (main panel) and the sense of immersion were similarly praised, with a majority of the ratings being in the “Excellent” and “Very Good” categories. Notably, questions related to interaction (Questions 6 to 11) showed that evaluators found the objects and buttons intuitive and easy to use, with 60% to 100% of the responses indicating “Almost always” or “Always”. These results suggest that the VR tool is user-friendly and effectively engages users through its design and interactive elements.

**Table 4.** Evaluation results of expert panel: usability characteristics.

Question	Excellent [%]	Very Good [%]	Satisfactory [%]	Regular [%]	Deficient [%]
1	60	40	0	0	0
2	60	40	0	0	0
3	60	40	0	0	0
4	40	60	0	0	0
5	80	20	0	0	0
	Never [%]	Almost Never [%]	Sometimes [%]	Almost Always [%]	Always [%]
6	0	0	0	60	40
7	0	0	0	40	60
8	0	0	0	40	60
9	40	60	0	0	0
10	0	0	20	20	60
11	0	0	20	40	40

Pedagogical integration (expert panel): The survey results for pedagogical integration (Table 5) highlight the strong alignment of the VR system with educational content and its effectiveness in meeting learning needs. All evaluators (100%) agreed that the electrical concepts presented were appropriate for teaching basic DC electrical circuits and that the images and videos related to the concepts were clear. The degree of interaction with the 3D objects within the game was rated highly, with 60% of the responses indicating “5” (the highest rating) and 40% indicating “4”. This suggests that the VR tool effectively engages students in interactive learning. Additionally, the circuit-building module was deemed to meet real electrical circuit practice needs to a great extent or completely by 60% of the evaluators. The implementation of the game as an innovative educational tool was also rated highly, with 60% of the evaluators believing it contributes to learning the fundamentals of DC electrical circuits completely. These findings affirm the effectiveness of the VR tool in enhancing pedagogical integration and providing an engaging and interactive learning experience, and the electrical concepts presented, in images, videos, 3D objects and symbols, were clear, relevant, and consistent for contextualization in the teaching of basic direct current electrical circuits.

**Table 5.** Evaluation results of expert panel: pedagogical integration characteristics.

Question	All [%]	Some [%]	None [%]		
12	100	0	0		
13	100	0	0		
Question	Excellent [%]	Very Good [%]	Satisfactory [%]	Regular [%]	Deficient [%]
14	60	40	0	0	0
<b>Question</b>	<b>5</b>	<b>4</b>	<b>3</b>	<b>2</b>	<b>1</b>
15	60	40	0	0	0
Question	Completely [%]	Very Good [%]	Satisfactory [%]	Regular [%]	
16	20	40	40	0	
17	60	20	20	0	

Safety (expert panel): The safety results from the survey of the evaluators (Table 6) show a strong consensus on the safety of the VR tool and a lack of adverse effects. No evaluators reported detecting any errors during gameplay (100% “no”). Additionally, a majority of the evaluators (80%) indicated that they “never” experienced physical effects such as dizziness, nausea, or headaches while manipulating objects in the game, with the remaining 20% reporting “almost never” experiencing such effects. No evaluators reported that the guide induced them to make mistakes during immersion, nor did they encounter any obstacles or conflicts that hindered the completion of activities (100% “no”). Regarding the virtual reality learning environment, no errors in coding or effects related to vertigo or visual fatigue in the user were detected. These results suggest that the VR tool is not only safe but also well-designed to prevent common issues associated with VR usage, such as physical discomfort and navigation errors.

**Table 6.** Evaluation results of expert panel: safety characteristics.

Question	Yes	No			
18	0	100			
20	0	100			
21	0	100			
Question	Always [%]	Almost Always [%]	Sometimes [%]	Almost Never [%]	Never
19	0	0	0	20	80

The evaluation of the VR application involved a comprehensive assessment of its usability, pedagogical integration, and safety, utilizing a survey instrument detailed in Supplementary Materials File S1. This study initially included ten students from the “Fundamentals of Electrical Circuits” course and was later expanded to include an additional 17 students, resulting in a total of 27 student participants.

Usability and interaction (students): The usability results (Table 7) indicate a high level of satisfaction among the students regarding the VR system. For the preliminary instructions, 94% of the students rated them as either excellent or very good, suggesting that the guidance provided was clear and effective. Similarly, in-game instructions were highly rated, with 71% of the students giving them excellent or very good ratings, indicating that the controls and object handling were well-explained. Satisfaction with the 3D environment design was also high, with 89% of the students rating it as excellent or very good, reflecting

the immersive and visually appealing nature of the game. The 2D interface design was positively received by 94% of the students, suggesting that the main panel’s design elements were user-friendly. Lastly, the sense of immersion was rated highly by 94% of the students, highlighting the effectiveness of the VR environment in engaging students. The interaction section showed that while most students found the interaction with objects and buttons intuitive, a small percentage faced occasional challenges, potentially due to varying levels of familiarity with VR technology. The terminology and symbols used were clear to the majority, but a few students might benefit from additional context or explanation. Navigation through the main screen was smooth for most, though some adjustments could enhance the experience further. Although most students did not encounter difficulties during gameplay, ensuring consistent ease of use for all users remains important. The time allocated for each module and the feedback provided were generally sufficient, but minor tweaks could improve the overall learning experience.

**Table 7.** Evaluation results of student participants: usability and interaction characteristics.

Question	Excellent [%]	Very Good [%]	Satisfactory [%]	Regular [%]	Deficient [%]
1	65	29	0	6	0
2	53	18	0	0	0
3	71	18	12	0	0
4	59	35	6	0	0
5	53	41	6	0	0
	Never [%]	Almost Never [%]	Sometimes [%]	Almost Always [%]	Always [%]
6	59	29	6	6	0
7	82	12	6	0	0
8	59	29	12	0	0
9	6	6	18	41	29
10	12	53	18	18	0
11	41	18	24	12	6

**Pedagogical integration (students):** The results for pedagogical integration (Table 8) indicate a strong alignment between the VR system’s educational content and the students’ learning needs. A significant majority (94%) of the students found the electrical concepts appropriate for teaching basic DC electrical circuits, suggesting that the content was well-chosen and relevant. The clarity of images and videos was affirmed by 82% of the students, indicating that visual aids were effective in enhancing understanding. The 3D objects used to conceptualize elements and symbols were highly rated by 71% of the students as excellent or very good, reflecting the success of the visual representation in aiding comprehension. The degree of interaction with the 3D objects was rated highly, with 82% of the students giving the highest scores, suggesting that the interactive elements were engaging and functional. Most students felt that the circuit-building module met the needs of real electrical circuit practice, with 82% affirming this to a great extent or completely, highlighting the practical applicability of the VR tool. Additionally, 100% of the students believed the game contributed significantly to learning the fundamentals of DC electrical circuits, emphasizing the educational value of the VR environment. These results suggest that the VR tool effectively bridges theoretical knowledge and practical application, possibly due to its immersive and interactive nature, which enhances engagement and retention.

**Safety (students):** The safety results (Table 9) suggest that the VR system is generally safe and stable, with a few areas requiring attention. A slight majority (53%) of the students did not detect any errors during gameplay, indicating overall stability, though nearly half of them did report some issues, suggesting occasional glitches that need addressing. Most

students (53%) never experienced physical effects such as dizziness or nausea, but 47% reported almost never or sometimes experiencing such effects, indicating that while the VR environment is mostly comfortable, some students may have sensitivity to VR experiences. Importantly, all students reported that the guide did not induce any mistakes during immersion, reflecting clear and effective instructions. Additionally, 82% of the students did not encounter any obstacles or conflicts that hindered the completion of activities, demonstrating a well-designed and smoothly functioning VR environment. These findings suggest that while the VR system is largely safe and user-friendly, ongoing monitoring and refinement are essential to ensure a consistently positive experience for all users. The occasional physical effects reported may be due to individual differences in susceptibility to VR-induced discomfort, highlighting the importance of offering guidelines for optimal use and ensuring that VR sessions are appropriately timed to minimize any adverse effects.

**Table 8.** Evaluation results of student participants: pedagogical integration.

Question	All [%]	Some [%]	None [%]
12	94	6	0
13	82	18	0

Question	Excellent [%]	Very Good [%]	Satisfactory [%]	Regular [%]	Deficient [%]
14	53	18	29	0	0
Question	5	4	3	2	1
15	41	41	18	0	0

Question	Completely [%]	Very Good [%]	Satisfactory [%]	Regular [%]
16	29	18	29	0
17	76	41	18	0

**Table 9.** Evaluation results of student participants: safety.

Question	Yes	No
18	47	53
20	0	100
21	82	18

Question	Always [%]	Almost Always [%]	Sometimes [%]	Almost never [%]	Never
19	0	12	6	29	53

#### 4. Discussion

The development of this research underscores the transformative role of virtual reality (VR) in educational settings, emerging as a robust tool in the teaching and learning processes. Consistent with the observations by Escartín [46], VR is recognized not merely as a technological advancement but as a fundamental shift in the educational paradigm, supporting a more interactive and engaging learning process. Programs in developed countries have already begun integrating VR across various educational levels, reflecting a global trend towards immersive learning environments.

This study extends the current understanding of VR by demonstrating that a VR-based learning environment significantly enhances immersion and interaction with three-dimensional objects. This enhancement, as described by Miguélez-Juan et al. [47], promotes a realistic simulation of complex virtual worlds where users engage in real-time through

tailored electronic devices, thereby boosting motivation and providing a lifelike experience during theoretical–practical activities. Furthermore, this approach mitigates traditional risks associated with electrical circuit training, such as electrical hazards and equipment damage, by providing a safe simulated environment for experimentation and learning.

The feedback from this study's VR laboratory experience aligns with findings by Botella et al. [48] and Paszkiewicz et al. [49], which reported a high approval rating for VR's application in primary education due to its capacity to safely replicate inaccessible or hazardous real-world environments. This correlation not only validates VR's utility in diverse educational settings but also highlights its potential in specialized fields such as electrical engineering education. Feedback from this study's VR laboratory experience aligns with findings by Singh [50] and Tanaka et al. [51], which reported a high approval rating for VR's application in electrical substation training due to its capacity to safely replicate inaccessible or hazardous real-world environments. This correlation not only validates VR's utility in diverse educational settings but also highlights its potential in specialized fields such as electrical engineering education.

Despite these advancements, challenges remain, particularly concerning the infrastructure required for implementing VR. The need for high-performance computers to process and display intricate simulations remains a significant barrier [46,51]. This infrastructure challenge is crucial for future research directions, as addressing these barriers could expand VR's accessibility and applicability.

Moreover, while this study focused on the benefits of VR in enhancing the understanding of direct current electrical circuits, its application in the social sciences and other fields suggests a broader potential. Future studies could explore interdisciplinary applications of VR, examining its impact on various educational outcomes and its integration into different curricular areas. Therefore, the findings from this research not only reinforce the efficacy of VR in enhancing educational experiences but also advocate for its broader adoption in curriculum design. As digital literacy becomes increasingly vital in higher education, VR's role in this domain is likely to expand, necessitating ongoing research into its integration, scalability, and long-term educational impacts.

Looking ahead, further research should focus on overcoming technological and infrastructural barriers to make VR more accessible across educational sectors. Additionally, studies could explore the long-term impacts of VR on learning retention and student engagement across diverse demographic groups. Another promising area for future investigation is the development of customizable VR content that educators can tailor to specific learning objectives and student needs, potentially transforming VR into a standard teaching tool across educational levels.

The constant advent of emerging technologies is creating disparities in access and usage within educational settings, exacerbating issues of digital illiteracy and constraining the pedagogical potential these advancements might offer. Often, traditional classroom strategies prioritize the transmission of theories and concepts in ways that isolate students from engaging and participatory learning processes. Such methods, which emphasize rote memory, repetition, and obedience, often position the teacher as the sole arbiter of educational success, thereby diminishing student motivation and hindering the development of knowledge, skills, and values. Conversely, the integration of emerging technologies, underpinned by educational theories such as constructivism and linked with innovative pedagogical methods, offers alternative teaching and learning modalities. Technologies like virtual reality introduce dynamic and disruptive learning environments that can significantly enhance student motivation, acknowledging and building upon students' prior knowledge and fostering the development of skills through problem-solving in real-world contexts [52]. Soler [53] highlights that while virtual reality holds substantial educational promise, it requires further research to optimize its content and extend its application broadly.

The survey results underscore the high usability, effective pedagogical integration, and robust safety of the VR system. A significant majority of the students rated the preliminary and in-game instructions, as well as the 3D environment and 2D interface

design, as excellent or very good, indicating clear guidance and a user-friendly design. The sense of immersion was highly rated, with only minor interaction challenges noted. The pedagogical integration was strong, with most students finding the electrical concepts appropriate and the interactive 3D objects effective in enhancing understanding. The circuit-building module was well-received, meeting practical needs and contributing significantly to learning the fundamentals of DC electrical circuits. Security-wise, the system was stable and comfortable for most users, though a few reported minor physical effects. These findings validate the VR tool's effectiveness in enhancing educational experiences and highlight areas for continuous improvement, aligning with this study's objectives of exploring VR's potential in transforming teaching and learning dynamics in electrical engineering education.

The comparison of survey results between the expert panel and the students revealed several key insights into the usability, pedagogical integration, and security of the VR tool. Both groups rated the preliminary and in-game instructions highly, with the expert panel giving 60% "Excellent" ratings and students rating them at 94% for preliminary instructions and 71% for in-game instructions as excellent or very good. This suggests effective guidance for users, though the students showed slightly higher satisfaction. Satisfaction with the 3D environment and 2D interface design was also high for both groups, indicating that the VR tool's visual and interactive elements were well-received. The experts and students alike found the interaction intuitive, with a majority indicating "Almost always" or "Always", though a few students faced occasional challenges, possibly due to varying levels of familiarity with VR technology. In terms of pedagogical integration, both groups recognized the VR tool's effectiveness in presenting electrical concepts, with 100% of the experts and 94% of the students affirming its appropriateness. The experts rated the degree of interaction with 3D objects highly, and 71% of the students rated it as excellent or very good, reflecting successful engagement. Most notably, 60% of the experts and 82% of the students believed the circuit-building module met real practice needs to a great extent or completely. Regarding security, both groups reported minimal issues, with the experts indicating no errors or physical effects and most students reporting similar comfort levels, though a few noted occasional dizziness or nausea. These findings suggest that the VR tool is well-designed, user-friendly, and effective in enhancing learning, though ongoing refinement and attention to individual user experiences could further optimize its impact. The slight differences in ratings between the two groups may be attributed to the experts' familiarity with VR technology and educational tools, compared to students' varying levels of prior exposure and experience.

Consequently, this study explores the potential of VR to transform educational environments, focusing on how immersive technologies can enhance teaching and learning dynamics. By simulating realistic environments, VR significantly improves upon traditional educational methods. It provides students with immersive and interactive experiences that are crucial for understanding and retaining complex concepts, such as electrical circuits. This research contributes to the evolving understanding of how VR can be effectively integrated into educational methodologies to facilitate deeper learning.

Theoretically, this research aligns with constructivist learning theories which emphasize active learning through experience and interaction, rather than a passive absorption of information. VR allows students to 'learn by doing' in a risk-free environment, which is particularly beneficial in technical disciplines where practical experience is crucial but often constrained by access to resources or safety concerns.

Practically, the findings from this study demonstrate VR's potential to increase engagement and motivation among students, which are critical factors in educational success. By incorporating VR into the curriculum, educators can offer students a more engaging learning experience that not only improves comprehension but also encourages continuous learning and curiosity.

Based on the results of this study, the following are recommended for the application of VR in educational settings: 1. the integration of VR into existing curricula to provide

students with hands-on experience in a virtual environment, thereby enhancing their understanding of theoretical concepts; 2. the development of customizable VR content that educators can tailor to specific educational needs and learning outcomes, making VR a versatile tool across various subjects; and 3. a continuous evaluation and adaptation of VR applications in education to ensure they meet the evolving technological standards and educational requirements. These recommendations aim to assist educators and policymakers in leveraging VR technology to transform educational environments and meet the diverse needs of students. By doing so, VR can play a pivotal role in bridging the gap between traditional education methods and the digital future, making learning more accessible, engaging, and effective for everyone.

## 5. Conclusions

Virtual reality (VR) has emerged as a significant advancement in educational technology by enhancing simulation, immersion, and interaction with three-dimensional objects. These elements are essential for achieving educational objectives, particularly in technical disciplines such as electrical engineering. This study demonstrates VR's transformative impact, facilitating hands-on, interactive learning experiences that significantly enhance comprehension and engagement, especially in the study of electrical circuits.

During the testing of the VR game "The Virtual Lab", no programming errors were identified that compromised user safety, nor were instances of vertigo or visual fatigue reported. This confirms the game's safety and comfort for educational use. It is recommended that the use of this virtual environment be moderated, with sessions ideally kept under thirty minutes, particularly for inexperienced users or those with visual and cognitive disabilities.

The immersive VR game surpasses traditional educational methods such as video games and educational software, particularly in boosting motivation, concentration, and the incorporation of gamification elements. In the context of electrical circuits, VR supports the acquisition of complex scientific knowledge more effectively and significantly enhances learner motivation and attention.

The integration of VR into classrooms has proven to promote equity by providing students from diverse backgrounds access to innovative learning tools. This inclusivity is crucial for creating an equitable educational environment where all students can benefit from advanced technological tools and engage more effectively with challenging subjects like electrical circuits.

A major challenge in expanding VR in education is the need for adequate infrastructure, such as high-performance computers and specialized software, necessary to support the sophisticated simulations required for teaching complex topics like electrical circuits. This infrastructure challenge underscores the importance of technological readiness in realizing the full benefits of VR in education.

Future research should focus on overcoming these technological barriers to make VR more accessible and feasible for widespread educational use. Further studies should explore the long-term impacts of VR on learning outcomes, including retention rates and the development of practical skills in electrical engineering, to provide deeper insights into VR's comprehensive benefits and challenges within the educational sector.

The practical implications of this study are extensive, particularly in the field of electrical engineering, where VR enables a hands-on learning experience that traditional methods cannot replicate. By integrating VR technologies into the curriculum, educators can enhance educational effectiveness and better align learning experiences with educational objectives. A continuous evaluation and adaptation of VR applications are recommended to ensure their ongoing relevance and efficacy, making learning more accessible, engaging, and effective for students of all backgrounds.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/fi16080279/s1>, Supplementary Materials File S1: Survey Instrument for Evaluating Usability, Pedagogical Integration, and Safety of the VR Application; Figure S1: GUI coding structure; Figure S2: GUI coding structure continued.

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