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Using Mixed Reality (MR) as an Emerging Technology for Improving Higher Education: Analysis of Mental Workload

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Abstract

This study aims to evaluate the mental workload perceived by students when using Build_3D, a mixed reality (MR) application, as an educational tool for learning PC and smartphone hardware, as well as to analyze teachers' perceptions of its impact on the teaching process. The NASA-TLX tool was applied to measure mental workload in 60 students, assessing six dimensions: mental demand, physical demand, temporal demand, perceived performance, effort, and frustration level. Additionally, qualitative observations were collected from teachers regarding the use of MR in practical learning environments. The results show that the perceived performance dimension achieved the highest score, highlighting the application's effectiveness in improving learning outcomes. Mental and temporal demands were moderate, while effort, frustration, and physical demand were low. Teachers noted that Build_3D enhances practical learning by enabling the repetition of complex tasks and fostering student motivation through immersive experiences. As a novel contribution, the study highlights the capacity of MR tools to integrate theoretical and practical concepts in an interactive environment, reducing cognitive load and promoting autonomous and personalized learning.

Keywords:

Active Learning; Authentic Learning; AR Application; AR in Learning; Higher Education; Oculus; Mental Workload; Mixed Reality; Nasa-TLX.

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1- Introduction

Higher education has undergone significant transformations in recent decades, mainly driven by the advancement of emerging technologies [1, 2]. Among these technologies, Augmented Reality (AR) and Mixed Reality (MR) have gained increasing interest as innovative tools capable of enhancing teaching and learning processes [3–5]. The ability of AR and MR to overlay digital information on the real world, creating interactive and immersive experiences, has opened new possibilities in the educational field [6, 7]. The use of these technologies can not only help visualize complex concepts more clearly but also improve student engagement, potentially leading to better information retention and understanding of topics [8]. One of the main benefits of AR and MR in education is their ability to offer personalized and adaptive experiences [3]. Unlike traditional teaching methods, where all students receive the same instruction, these technologies allow each student to progress at their own pace and explore content according to their needs and preferences [9].

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In this context, AR is a technology that overlays digital information (such as graphics, text, or images) on the real world, but unlike MR, it does not allow virtual elements to interact as deeply with physical objects [10]. In AR, users see the real world with added layers of digital information, but virtual objects do not have the same level of interaction or integration with the physical environment [11]. On the other hand, MR refers to the merging of physical and virtual world elements, allowing real-time interaction between the two [12]. In an MR environment, digital objects not only coexist with those in the real world but can also interact meaningfully with them [13]. This means that users can manipulate both physical and virtual objects within a shared space, creating an immersive and highly interactive experience [14]. Fields where these technologies can have a significant impact on teaching include academic areas that traditionally depend on access to expensive or hard-to-obtain components. Such is the case in medicine [15–17], interior design [18], mathematics [19], geometry [20], chemistry [21], and others.

However, despite its growing adoption, there are limitations in the literature regarding its impact on students' cognitive load and its effectiveness in practical and technical areas [22]. Previous studies have explored the ability of AR and MR to visualize complex concepts and personalize educational experiences [23, 24]. However, few works have thoroughly analyzed the challenges related to interface design, information presentation, and mental load in MR environments [25]. To address this gap, this study evaluates the impact of the Build_3D application, which was designed to operate on immersive augmented reality glasses (Meta Quest 3). This application can be used to learn about the assembly and functioning of hardware components in a computer and a smartphone. Build_3D allows students to virtually manipulate hardware components, such as processors and memory modules, offering a hands-on experience without physical or financial constraints. Students can practice assembling and disassembling a smartphone as many times as needed to fully understand the concepts, without the risk of damaging expensive components or running out of materials. Furthermore, Build_3D provides instant feedback, allowing students to correct mistakes in real-time and continuously reinforce their learning. Augmented reality stands out from other digital technologies in education due to its ability to offer more realistic and practical experiences, which can be particularly useful in learning technical subjects.

Despite these benefits, the implementation of MR technology applications for learning also presents challenges. Interface design, the quality of interactions, and information presentation are factors that can influence students' mental load [26]. If the interface is too complex or the information is poorly structured, students may feel overwhelmed, which could increase cognitive load and reduce the effectiveness of learning [3]. Therefore, it is essential to conduct a rigorous evaluation of the user experience to ensure that the technology is not only engaging but also accessible and easy to use [27]. This paper uses the NASA-TLX tool to measure mental load in students, analyzing dimensions such as mental, physical, temporal demand, effort, frustration, and perceived performance [28, 29]. In addition, it gathers teachers' perceptions regarding the integration of MR in practical learning. The findings aim to provide recommendations for the effective implementation of MR in educational settings, contributing to the design of technologies that optimize user experience and learning.

The objectives of this research were:

Objective 1: To analyze whether students experience any level of frustration, effort, and temporal, mental, and physical demand when using an MR application to support education.

Objective 2: To propose recommendations for the implementation of MR technology applications to support education.

The theoretical approach of the research is a crucial aspect in understanding how Mixed Reality (MR) impacts students' mental load in the educational context. To address this, it is essential to consider Cognitive Load Theory and the conceptual framework underlying this research [30]. Cognitive Load Theory (CLT), proposed by John Sweller in 1994, asserts that human cognitive processing capacity is limited, and that learning is affected by the amount of cognitive load imposed during a task [31, 32]. In the context of this study, NASA-TLX is used to assess whether the use of Build_3D in education leads to cognitive overload, which could result in frustration, excessive effort, and a decrease in learning effectiveness. Based on the results, it can be identified that the use of MR applications not only facilitates content comprehension but also maintains a balance in cognitive load. Another relevant theory influencing this study is experiential learning theory, which suggests that learning occurs when students go through a cycle of concrete experience, reflection, abstract conceptualization, and active experimentation [32, 33]. In the case of MR applications, students have the opportunity to interact with content in an immersive and active way, facilitating an educational experience that adapts to their individual needs [34]. Build_3D, by offering an interactive environment, allows students to engage in practical experiences that might be more difficult or impossible to achieve in a traditional classroom. This aligns with the idea that immersive experiences can reduce cognitive load by making learning more tangible and accessible, allowing for a better understanding of abstract concepts [35].

This section introduces the reader to the use of MR technology in education, the problem addressed by the research, and the theories supporting it. The following sections of this paper are organized as follows: Section 2 reviews the application of MR technology in education. Section 3 details the research methodology employed. Section 4 presents the research findings. Section 5 discusses these results in depth. Section 6 outlines the study's conclusions, and Section 7 suggests directions for future research.

2- Mixed Reality Technology in Education

In the educational field, this technology has the potential to enhance the learning experience by providing immersive, interactive, and personalized environments, facilitating the understanding of complex concepts. MR has been used to improve learning in disciplines that require practical skills and the visualization of abstract concepts. For instance, in medical sciences, students can practice surgical procedures in a controlled environment, where virtual objects simulate organs and tissues, enhancing their understanding without risks to patients [15, 16]. Students can interact with 3D anatomical models using devices like the Meta Quest, allowing them to explore the human body in real time, view complex structures such as the cardiovascular system, or practice medical procedures [14, 36]. MR can also be used to visualize and modify 3D models of buildings or structures in real time. This facilitates collaboration between architecture and interior design students and instructors when reviewing projects in these fields [37, 38]. MR technology allows students to interact with molecules, chemical compounds, and biological processes in an immersive way. This improves the visualization of molecular structures and helps in the understanding of complex chemical reactions. Students can manipulate atoms and molecules in a virtual environment or observe how chemical reactions occur on a microscopic level using MR devices [39, 40]. Moreover, MR is used to teach engineering students how complex machines or electrical systems work, allowing for more tangible interaction with models instead of traditional flat diagrams. Students can virtually disassemble and reassemble engines, inspect internal components, and simulate their operation [41, 42]. Finally, in the field of history, MR enables students to virtually visit historical sites, interact with historical figures, or experience past events in an immersive way, such as virtual museum tours and archaeological sites. Students can explore virtual replicas of ancient artifacts and reconstructions of historical cities [43–45].

The benefits of MR in the educational field are numerous. One of the most notable examples is the ability to offer immersive and personalized learning experiences [3, 13]. These environments can enhance knowledge retention by engaging multiple senses in the learning process [3]. The interaction with 3D objects and the ability to manipulate them in real time allows students to explore complex concepts from a practical perspective [14, 46]. Additionally, MR facilitates collaboration among students; users can share a virtual environment while interacting with objects and each other, promoting teamwork and collaborative learning [3, 4, 6]. In disciplines like engineering, where group work is fundamental, this technology has been shown to improve communication and problem-solving skills [14]. Another significant aspect is MR's ability to adapt to different learning styles [9]. By combining visual, auditory, and kinesthetic elements, MR can personalize content according to the needs of each student, which is particularly beneficial for those with learning difficulties [9].

3- Methodology

For this research, an experimental methodology was used with the help of the NASA-TLX tool survey and the help of teachers from a higher education institution, this can be seen in Figure 1.

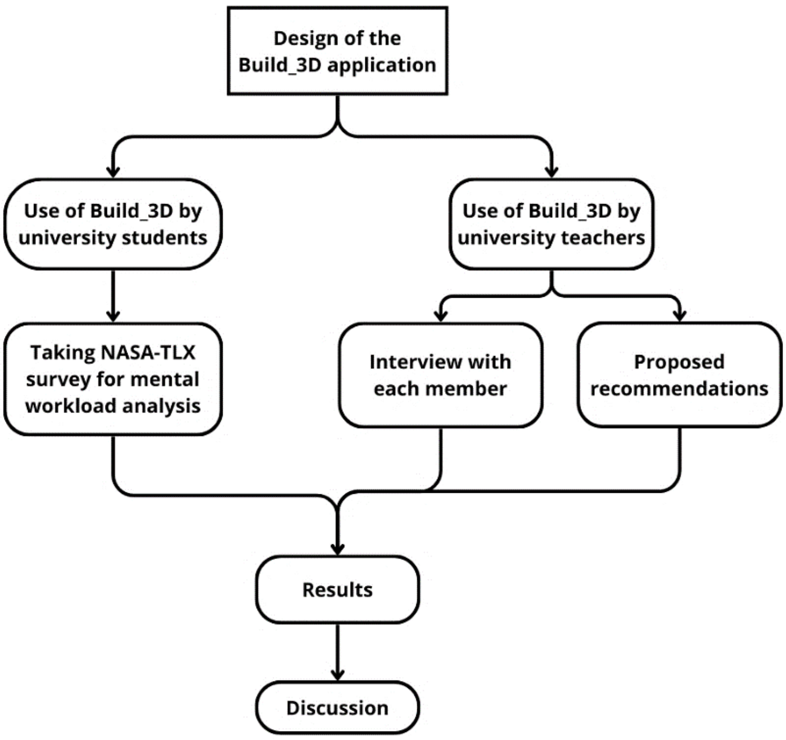

Figure 1. Experimental research methodology

3-1-Mobile Augmented Reality Application Design

Design Process

This project was born from the idea of building a tool focused on learning the components and assembly of hardware, such as a computer and a smartphone, using MR technology. To achieve this goal, two challenges had to be overcome with innovation and creativity. The first was the assembly process of the elements (PC and smartphone), and the second was designing an interface to ensure an adequate user experience. The Build_3D application allows users to pick up components and assemble them correctly with natural interactions—meaning as frictionless as possible and closely resembling how it would be done in real life. The natural way to do this is for users to manipulate the objects by using their hands and making gestures such as "grabbing" and "releasing," allowing them to place, drop, or rearrange components. To achieve this, custom software and code were used that work with the integrated cameras of the Meta Quest 3 to detect the silhouette of the hands, finger positions, curvature, flexion, finger separation, and opposition. Figure 2 shows the four positions that fingers can assume to design an MR application suitable for practical use. Curvature detects how bent the fingers are at their joints. Flexion detects the degree, in angles, to which the knuckles are bent towards the palm of the hand. Separation detects when adjacent fingers are spread apart, forming an angle. Finally, opposition detects how close the tip of one finger is to the thumb, applying only to the index, middle, ring, and little fingers.

For the development of MR software, two main points are proposed:

1. **3D Objects:** These are placed in the scene to request an action based on the user's familiarity with real-world objects. For example, using a red button signal to the user that they should press it to interact with that 3D element and expect something to happen. This is particularly important for users who are new to MR.
2. **Spatial Text:** The application includes a feature that displays detailed information about each component in the form of text. The user can grab the text like a 3D object to read it, but when releasing it, they might place it at an angle that is difficult to read or even invisible. To resolve this issue, a text tracking system was implemented that follows both the object and the user, ensuring the text remains readable.

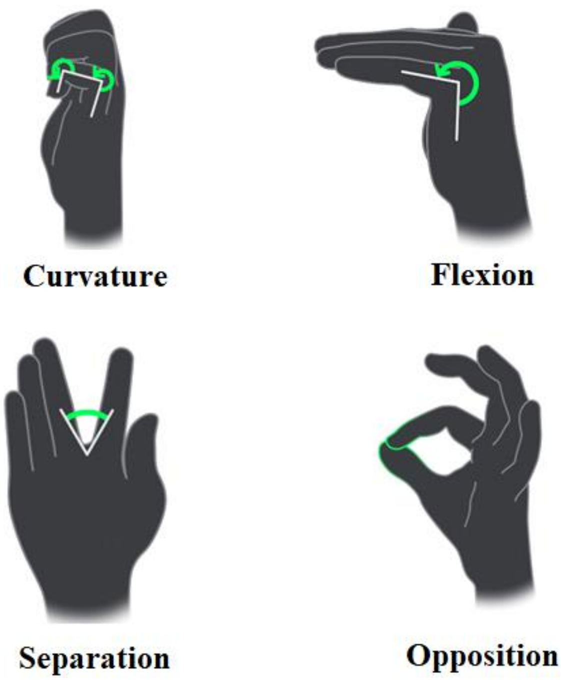

Figure 2. **Finger position**

Requirements

The development focused on both an educational perspective and the user experience. Several requirements need to be met, as shown in Table 1. It is important to address user comfort, intuitive use, and the visual language that serves as a guide for interactions. Additionally, Table 2 presents the technological tools used, and Table 3 details the libraries and dependencies employed for the design of Build_3D.

Table 1. Usability Requirements for the Application

Requirement	Description
Educational Content	Spatial computation for MR (3D) representation of the internal elements of a PC and a smartphone, as well as interactive educational interaction to illustrate component assembly.
Visual Language	3D button elements that must be pressed manually to perform an action. Palette with selection options for internal components of a PC and smartphone. Positioning of components indicated by a hologram with the shape of the component, which activates only when the user grabs one of the elements.
Convenience and Optimizations	To avoid dizziness from low visual quality or performance drops, code, execution, and resources are optimized using: Programming with loops and optimized element searches: • Programming with loops and optimized searches • Handling active or inactive elements dynamically based on activity, where each element has its own physics and responds to these interactions defined by scripts • 3D elements with techniques to reduce polygons and balancing of details • Rendered by software, balanced graphics, lights, and shadows for better performance
Comfort and Usability	Interaction is done through manual gestures, hand pose detection, and similar techniques of human-computer interaction to reduce user friction.
Shaders	To indicate that a PC component is placed in a specific place, when the user grabs the component, a hologram shows the correct location and alignment for that component. This is achieved through "Shaders," which are programs that give instructions to the device's chip on how to render pixels. This enables effects such as holograms, transparency, metallic reflections, among others.

Table 2. Technological Tools

Technology Name	Description
Unity 2022.3.10f1	Versatile game engine with features for building 2D, 3D, VR, AR, and MR projects with export capabilities to multiple platforms, including Mobile devices, Web, among others. It allows programming with components called "Scripts" written in C#. The following base configuration was used: • Export platform: Android • Texture compression: ETC2 (GLES 3.0) • Compression method: LZ4 • Render pipeline: Built-in
Visual Studio Code	Source code editor developed by Microsoft for Windows, Linux, macOS, and Web. Visual Studio Code was chosen for being lightweight and highly customizable. Extensions used: • Unity: Integrated development experience and C# Dev Kit for Unity projects • IntelliCode for C# Dev Kit: Includes assistance for C# development • C#: Support for C# language development • C# Dev Kit: Solution explorer and testing management
Blender 3.3.21.0	Free, open-source 3D modeling software used for: • Construction of necessary elements • Optimization and retopology: Techniques to reduce polygon count for a smoother experience

Table 3. Libraries and Dependencies Used

Name	Description
Meta MR Utility Kit	Utilities and tools at the API scene level to execute operations dependent on the spatial component of the physical space.
Meta XR All-in-One SDK	Set of all Meta SDKs that include features from advanced rendering, social functions, and compatibility to build immersive experiences in VR and MR. Includes: • Meta XR Core SDK • Meta XR Audio SDK • Meta XR Haptics SDK • Meta XR Interaction SDK • Meta XR Interaction SDK • Meta XR Platform SDK • Meta XR Voice SDK • Meta XR Simulator • Meta Mixed Reality Utility Kit
Meta XR Audio SDK	Provides spatial audio features for immersive applications.
Meta XR Core SDK	Provides the latest features to create immersive experiences for MR devices, such as Passthrough, Anchors, and Scene Understanding.
Meta XR Interaction SDK	Provides the core implementation of interaction models along with shaders, materials, and necessary prefabs
Meta XR Simulator	Allows visualizing changes in the project without needing a physical device or building the project.
Oculus XR Plugin	Provides support for input reception and display of information for Oculus devices.
XR Plugin Management	Provides simple management of extended reality (XR) plugins. Manages and offers loading assistance, initialization, configuration, and build support.

Development Methodology

The SCRUM methodology was used due to the nature of the project, which required incremental progress to test interactions during the development phase. Iterations were defined based on the requirements needed to build the application, there were six iterations over eight weeks, based on the knowledge and mastery of the technologies used.

Table 4. Scrum Iterations with Functionalities

Iteration	Description	Priority (1-10)	Duration (weeks)
1	Acquisition of 3D resources: PC components	10	1
2	Acquisition of 3D resources: Smartphone	10	1
3	Optimization of 3D resources: Reduce polygon count	7	1
4	Construction of PC assembly interaction	10	2
5	Construction of smartphone assembly interaction	10	2
6	Addition of detailed information per component	5	1
	Total time in weeks		**8**

Build_3D Application Visualization

Figures 3 and 4 provide a detailed visualization of the disassembly process of a PC and a smartphone. The background shown is an example of the ability to use RM ubiquitously, this academic support can be used in the classroom or outside the classroom. In these figures Build_3D uses MR to show key internal elements such as the battery, the motherboard, the camera module or the haptic engine, among others. This detailed segmentation allows users to see each component in its physical context, facilitating interactive learning about PC and smartphone hardware. Figure 5 shows that users can interact directly with device components, simulating actions such as removing the motherboard. This suggests that the application promotes a hands-on, immersive approach, which can improve information retention and motivation in learning. Direct manipulation of components in MRI space represents a significant advance over traditional teaching methods, such as textbooks or 2D simulations. In each scene, floating information panels are used to explain the hardware components. The texts provide technical descriptions of the purpose and characteristics of each component. This accessible presentation allows students to learn at their own pace, providing a personalized educational experience. The application is scalable in terms of the types of devices that can be disassembled, suggesting that it can be extended to other hardware or electronic devices, which would provide versatility for different training areas. Additionally, as seen in Figure 3 and 4, there is a mechanism (a red button) that can be pressed to switch between the visualization of a smartphone and a PC, highlighting a key feature in the design of Build_3D, which is its ability to teach various types of hardware technology. This shows that the application can be adjusted to different levels of knowledge, covering both simple components and more complex systems like those in a PC.

3-2- Experimental Protocol

Participants

This study involved 60 students and 20 faculty members from a higher education institution. All participants provided informed consent through a web-based form. The participants were selected through convenience sampling, due to their accessibility and availability to participate, without any compensation in this experiment. Of the 60 students, 17 (28%) were women and 43 (72%) were men, with participants aged between 18 and 19 years. On the other hand, all the faculty members who participated were men. Although the sample size is relatively modest, it is important to note that this study focused on evaluating the mental workload perceived by students when using an MR application for teaching the assembly of internal components of a PC and a smartphone. Additionally, although the sample mainly comes from a single university, it is noteworthy that this institution has a highly diverse and representative student population in terms of academic background and levels of knowledge.

Task

The experiment began with an introduction to the use of the Build_3D application. Participants were given the opportunity to ask questions and provide feedback and recommendations about the designed application.

- The students and faculty members used Build_3D, with each participant spending approximately 10 minutes assembling the PC and 10 minutes assembling the smartphone.
- Students completed the NASA-TLX tool questionnaire. The information obtained helped assess their perception of the mental workload associated with using MR technology as support in higher education.
- Faculty members were interviewed to gather their feedback on the MR tool and provided recommendations for the proper use and deployment of this technology as support in higher education.

These data can be valuable for educators and educational institutions looking to incorporate MR to innovate traditional methodologies and adequately address current challenges in the learning process.

Figure 3. Internal components of a PC

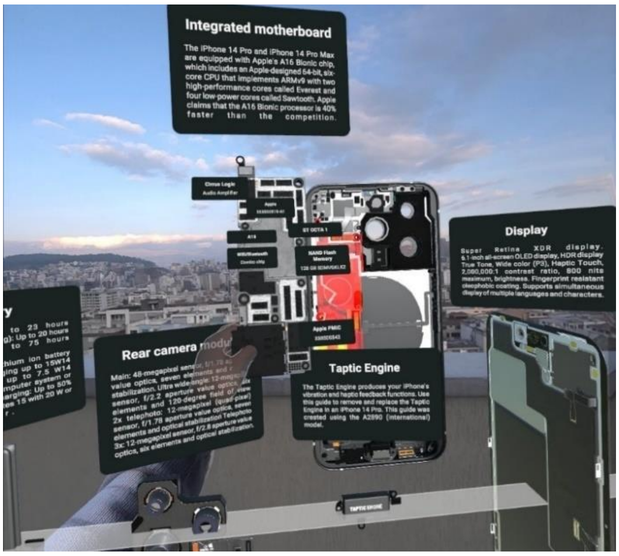

Figure 4. Internal components of a smartphone

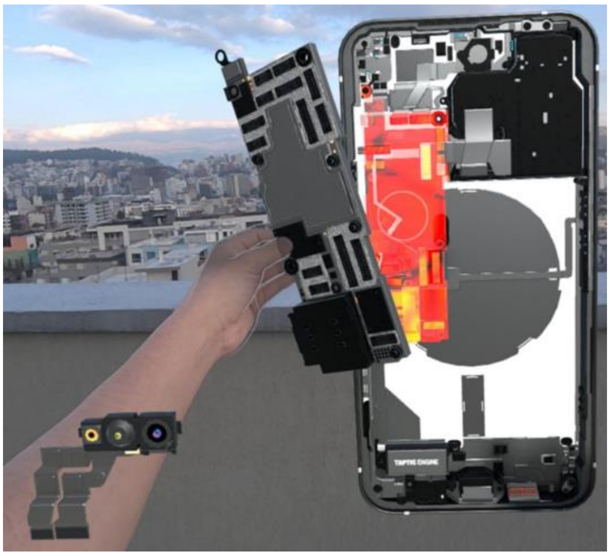

Figure 5. Manipulation of the internal components of a smartphone

Workload Analysis

The NASA-TLX is a widely used tool for measuring mental workload in various contexts, including work, academic, and technological environments, such as the use of MR and VR applications [28]. It was developed by NASA to assess the mental workload of operators in complex systems, such as pilots or air traffic controllers, and has since been extended to other areas [28]. The NASA-TLX measures perceived workload across six dimensions, which are defined in Table 5 [29].

Table 5. NASA-TLX rating dimension description

Title	Description	Scale
Mental Demand (MD)	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?	1-20
Physical Demand (PD)	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?	1-20
Temporal Demand (TD)	How much time pressure did you feel due to the rate or pace at which the tasks or task, elements occurred? Was the pace slow and leisurely or rapid and frantic?	1-20
Performance (PE)	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?	1-20
Effort (EF)	How hard did you have to work (mentally) to accomplish your level of performance?	1-20
Frustration Level (FL)	How insecure, discouraged, irritated, stressed, and annoyed or secure, gratified, content, relaxed, and complacent did you feel during the task?	1-20

4- Results

4-1- Students

To assess mental workload, the questionnaire provided by the NASA-TLX tool was used. The 60 participants responded to the survey based on the six dimensions associated with this tool, which are: Mental Demand (MD), Physical Demand (PD), Temporal Demand (TD), Performance (PE), Effort (EF) and Frustration Level (FL). As shown in Table 6, the PD dimension received the lowest score (1.35), PE received the highest score (13.60). Figure 6 shows graphically how students perceive each of the NASA -TLX dimensions. Responses were in the bottom 50% for all dimensions associated with the NASA-TLX survey except for PE. This indicates that students perceive that they can achieve better performance and learning outcomes when using Build_3D. The second highest score was for the TD dimension, meaning that the students' perceived time pressure to complete the application tasks was low. In third place was the MD dimension, which shows that using Build_3D was demanding at first but became easier as time progressed. In fourth place was the EF dimension, which indicated that students perceived a low level of mental effort when using Build_3D. In fifth place was the FL dimension, which showed that students experienced little frustration when using the application. Finally, it is evident that students perceived a very low physical demand (PD) to complete the tasks requested in Build_3D.

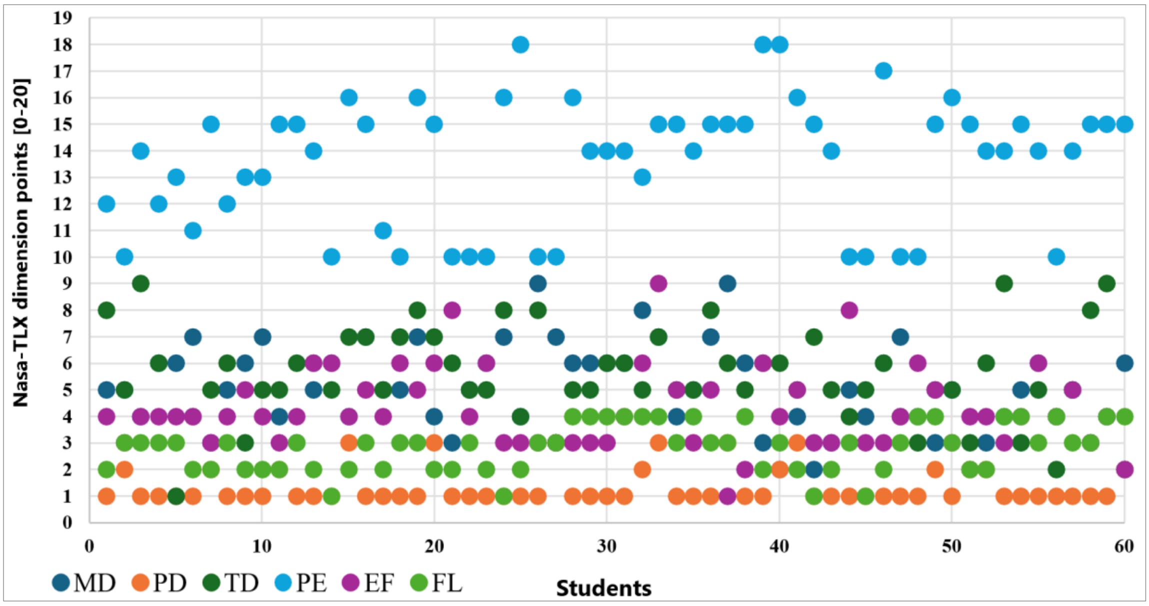

Figure 6. **Qualitative data on student responses to the six dimensions (maximum value: 20, minimum value: 1)**

Table 6. **Quantitative data to the six dimensions of NASA-TLX**

Students	MD	PD	TD	PE	EF	FL
60	5.08	1.35	5.50	13.60	4.23	2.80

Table 7 shows the six dimensions evaluated by the NASA-TLX tool grouped in pairs. Each cell indicates how many times a dimension was perceived as more significant compared to another in each pair. As shown in Table 7, MD (Mental Demand) is perceived as the most significant in the majority of comparisons, with high values, especially in the first columns (MD-PD; MD-EF; MD-FL). This confirms that students perceive the task as mentally demanding in most comparisons, indicating that Build_3D is cognitively challenging. PD (Physical Demand) is one of the least significant dimensions in almost all comparisons. There is only an increase in some columns (PD-FL; PD-TD; EF-PD), suggesting that students do not perceive a high physical workload when using Build_3D. TD (Temporal Demand) is also perceived moderately. Some columns have relatively high values (MD-TD; PD-TD; PE-TD; FL-TD; TD-EF), indicating that the time required to use the application is a concern in certain pairs, but it is not the most significant. In this context, PE (Performance) is the second most significant dimension after MD. The values are high in many cells (PD-PE; PE-TD; FL-PE; EF-PE), indicating that students perceive a high level of performance when using Build_3D to complete tasks. On the other hand, EF (Effort) is not perceived as a significant workload in many comparisons. This suggests that, although students perceive that minimal effort is required to complete the tasks in Build_3D, FL (Frustration Level) has moderate values in some comparisons but is not dominant in most pairs. This supports the idea that students do not experience high frustration when using the application as an educational aid.

Tables 8 and 9 present data on students' perceptions of using Build_3D. This data were used to calculate mental workload using the NASA-TLX tool. Table 8 shows an example of a quantitative calculation of perceived mental workload for participant one. Column A lists the weight of the six dimensions (MD, PD, TD, PE, EF, FL), that is, how many times they are repeated in Table 7. Column B shows the scores obtained for (MD, PD, TD, PE, EF, FL) from

Table 5. Columns C and D correspond to a simple formula between columns: B x 5 and C x A. The total quantitative score, which defines participant one's perception of mental workload when using the mobile application, was 495 points. This value, according to Table 8, indicates that participant one perceives a low mental workload when using the mobile application. Table 8 shows the total results of the mental workload level perceived by the 60 students who participated in this study. A total of 35 students (58.3%) perceives a low level of mental workload when using the application. The remaining 25 students (42.7%) perceive a medium level of mental workload when using the application. It is important to note that no student perceived a high level of mental workload associated with the use of the application. Therefore, it can be concluded that the majority of students perceive a low level of mental workload when using the mobile application.

However, Figure 7 shows the responses of the 60 students, which are concentrated between the values of 451.25 and 566.25, with very few students scoring higher, and only one student reaching 640 points. This indicates that students did not experience excessive mental workload when using the Build_3D application. Therefore, it is considered that this application can be used as a tool to support the teaching of hardware for electronic components.

Table 7. NASA-TLX dimension pair analysis

	MD-PD	MD-EF	MD-FL	MD-PE	MD-TD	PD-FL	PD-PE	PD-TD	PE-TD	EF-PD	FL-EF	FL-PE	EF-PE	FL-TD	TD-EF
MD	60	46	40	34	32	0	0	0	0	0	0	0	0	0	0
PD	0	0	0	0	0	35	5	28	0	12	0	0	0	0	0
TD	0	0	0	0	28	0	0	32	13	0	0	0	0	47	45
PE	0	0	0	26	0	0	55	0	47	0	0	56	47	0	0
EF	0	14	0	0	0	0	0	0	0	48	46	0	13	0	15
FL	0	0	20	0	0	25	0	0	0	0	14	4	0	13	0

Table 8. NASA-TLX evaluation Table (Example student 1).

Student 1	A. Weight	B. Score	C. Converted score (Bx5)	D. Weight score (CxA)
MD	2	5	25	50
PD	3	1	5	15
TD	2	8	40	80
PE	5	12	60	300
EF	2	4	20	40
FL	1	2	10	10
Total	**15**	**32**	**160**	**495**

Table 9. NASA-TLX scoreboard

NASA-TLX	Mental Workload Level
Score less than or equal to 500 points	35 students (Low)
Score greater than 500 points and less than 1,000 points	25 students (Medium)
Score over 1,000 points	0 (High)

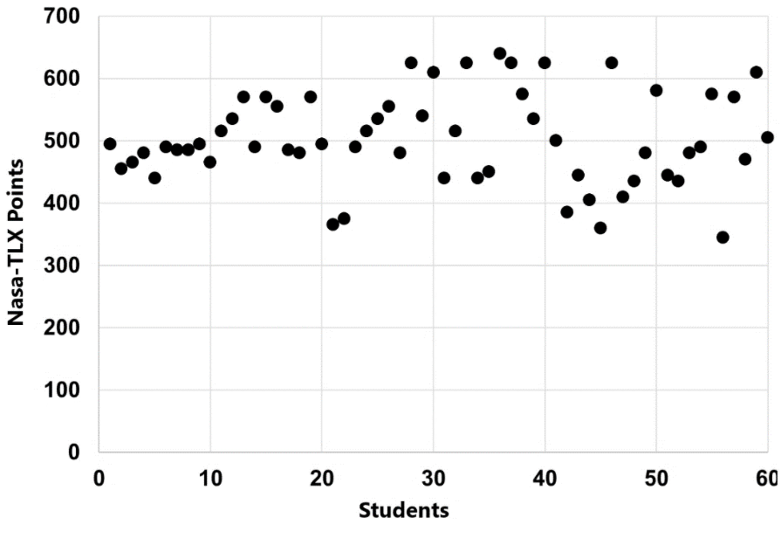

Figure 7. Responses of the 60 participants to the NASA-TLX survey

4-2- Teachers

The interviewed teachers agreed that the use of MR improves practical learning by enabling the repetition of complex tasks, such as hardware assembly, in a safe and controlled environment. Additionally, it reduces cognitive load by breaking tasks into manageable modules and allowing personalized learning paces. It also increases student motivation through immersive and engaging experiences, fostering autonomous learning, among other benefits. When using Build_3D with Meta Quest 3 to support the teaching of PC and smartphone hardware assembly, the teachers proposed several recommendations to maximize learning. Among them, they suggested gradually introducing MR technology with tutorials to help students become familiar with the controls and interface. It is important to integrate theoretical explanations with MR practical exercises, assigning specific tasks that cover different levels of complexity, and monitoring progress through practical assessments. All the recommendations are shown in Tables 10 and 11.

Table 10. Recommendations for the deployment of MR as support in education

Recomendation	Description
Adequate Infrastructure	Ensure that physical spaces are well adapted for the use of Meta Quest 3 and that there is sufficient free space so students can move safely while using AR.
Monitoring of Physical Safety	Supervise the use of the application and Meta Quest 3 devices so that students are using the equipment safely to avoid accidents.
Access to Devices	Ensure that all students have access to a Meta Quest 3 device or coordinate shared use in scheduled practice sessions, establishing schedules so all students can participate in learning activities.
Accessible Technical Support	Ensure there is a support team available to quickly resolve any problems students may encounter when using the MR application.
Use of Data Analysis for Personalization	Use data analysis to monitor students' progress and adjust the learning experience based on their performance, identifying behavior patterns and areas where students are experiencing difficulties.
Teacher Training	Train teachers in the use of Build_3D and AR technology, so they can guide students and solve technical problems that may arise during practice sessions.
Curricular Integration	Ensure that the implementation of MR technology is coherent with the educational curriculum. It is important that instructors are trained to integrate this technology into their teaching methods.
Maintenance and Updates	Keep both the Build_3D software and Meta Quest 3 devices updated to avoid compatibility problems or errors during practice sessions.
Complementing with Real Practices	Combine the use of Build_3D with real hardware assembly practices so students can acquire both theoretical and practical skills in a safe environment.

Table 11. Recommendations to avoid mental workload when using MR as support in education

Recomendation	Description
Content Modularization	Divide complex tasks into smaller, more manageable modules to facilitate information processing.
Provide Clear and Simple Instructions	Provide clear, concise, and easy-to-follow instructions to reduce cognitive overload.
Use of Visual and Multimedia Aids	Incorporate graphics and explanatory videos to reinforce concepts without overloading with textual information.
Immediate and Progressive Feedback	Provide immediate feedback after each activity to avoid the accumulation of errors.
Incorporate Breaks and Planned Pauses	Include suggested breaks to avoid mental fatigue during prolonged use and prevent cognitive fatigue.
Facilitate Personalization of the Experience	Allow students to progress at their own pace within the MR application. Offer personalization options to adjust the difficulty and duration of tasks, helping students feel more comfortable with the content and reducing cognitive overload.
Optimization of User Interface (UI) Design	Simplify the interface design to make it more intuitive and easy to navigate. UI elements should be clear and direct, avoiding overloading the user with too many options or simultaneous information.
Prior Training or Interactive Tutorials	Before students face complex scenarios in MR, provide simple practice tasks to familiarize them with the application. This will reduce mental and temporal demands.
Gamification of Tasks	Incorporate gamification elements to make cognitive tasks more fun and less overwhelming.
Facilitate navigation within the application	Simplify navigation to reduce mental effort when searching for resources within the application.
Continuous Usability Evaluations	Conduct periodic usability evaluations with students to obtain continuous feedback on the use of the MR application. This will allow for iterative improvements that meet the changing needs of the students.

5- Discussion

The theoretical approach of the research is anchored in two key theories: Cognitive Load Theory and Experiential Learning. These theories provide a deep understanding of how MR applications can impact learning, both positively and negatively, and offer a framework for assessing students' mental load when using these technologies. The encouraging results of the research, in which students report low mental workload, support the idea that, when implemented correctly, MR applications can enhance the educational experience by reducing cognitive load, fostering intrinsic motivation, and facilitating effective interaction with the content.

5-1- Objective 1

To analyze whether students experience any level of frustration, effort, and temporal, mental, and physical demands when using an MR application as educational support, the results obtained for each of the evaluated dimensions must be interpreted. The results show that FL (Frustration Level) is moderate in some comparisons but is not a dominant dimension in most of the evaluated pairs. This suggests that students do not experience high levels of frustration while using the application, which is a positive indicator for the user experience. The EF (Effort) perceived by the students is low or moderate in most comparisons. Students do not feel they need to exert much effort to complete the tasks, indicating that the application is accessible and does not excessively overload users in terms of personal effort.

The task is highly demanding at the cognitive level, as MD (Mental Demand) is the most significant dimension in most comparisons. This means that the application requires a considerable level of concentration and mental processing, indicating that it is cognitively demanding. PD (Physical Demand) is perceived as low in most cases, implying that the use of the application does not require significant physical effort. This is expected, given that the application focuses on cognitive tasks rather than physical activities. Although TD (Temporal Demand) is moderately present in some pairs, students do not perceive the time spent using the application as a limiting or highly stressful factor. This indicates that the time required to complete the tasks is manageable within the students' expectations.

The results confirm that, while the application is cognitively demanding, it does not generate significant levels of frustration, physical effort, or excessive temporal demand. The Build_3D MR application is effective as an educational tool without imposing a significant workload in terms of effort, frustration, or physical demands. This reinforces the idea that MR technology can be successfully integrated into education without negatively impacting students' well-being.

5-2- Objective 2

Table 10 addresses crucial aspects to ensure the effective and safe implementation of MR technology. First, adequate infrastructure is essential, as the use of Meta Quest 3 requires a physical environment that allows students to move freely without risks, ensuring an immersive experience without accidents. This is complemented by monitoring physical safety, emphasizing the importance of supervising the use of devices to prevent incidents. Access to devices is also a significant logistical challenge; it is vital to ensure that all students can use Meta Quest 3 equitably, either through individual access or by coordinating shared use during practical sessions. To ensure the continuity of the teaching-learning process, it is recommended to have accessible technical support available, which can quickly resolve any technical issues that arise, minimizing disruptions during class. The use of data analysis for personalization offers a more in-depth approach to monitoring student progress and adjusting learning experiences based on individual performance, enhancing the effectiveness of the educational process.

A key factor for successful deployment is teacher training, as educators need to be well-versed in Build_3D and MR technology to properly guide students and resolve technical issues in real-time. Likewise, curricular integration ensures that MR is not used in isolation but as an integral complement to the existing educational curriculum, reinforcing learning objectives through its coherent implementation. Maintenance and updates for both Build_3D software and Meta Quest 3 devices are essential to avoid compatibility errors and ensure that the system functions smoothly during practical sessions. The recommendation to complement virtual practices with real experiences ensures that students not only develop skills in virtual environments but also apply that knowledge in practical situations, reinforcing their theoretical and practical understanding of hardware assembly. Together, these recommendations enable the effective deployment of MR technology in education, ensuring that both students and teachers maximize its benefits while mitigating potential risks or technical challenges.

The use of Build_3D generates high cognitive demand and high perceived performance, indicating that these tools can be effective for advanced learning. However, moderate temporal demand and manageable effort suggest that it is important to properly structure activities and provide support during the use of these applications to avoid mental fatigue or time pressure. Table 11 provides key guidelines for optimizing the learning experience without generating cognitive overload in students. Content modularization is a fundamental strategy that allows complex tasks to be divided into smaller, more manageable modules, facilitating the assimilation of information and avoiding cognitive saturation. Complementing this with clear and simple instructions is essential, as confusing or lengthy instructions can increase cognitive demand. The use of visual and multimedia aids efficiently reinforces concepts without over-reliance on text, helping to reduce mental load by presenting information visually and making it easier to understand. Immediate and progressive feedback ensures that students can correct mistakes in real-time, avoiding the accumulation of problems that could cause frustration or confusion.

Another key recommendation is to incorporate breaks and planned pauses, which help mitigate mental fatigue caused by prolonged use of MR technology. Personalization of the experience also plays an important role by allowing students to progress at their own pace and adjust task difficulty, giving them more control and reducing the risk of feeling overwhelmed. Optimizing the graphic interface design is crucial for making navigation within the application intuitive and easy. A clear and direct design, avoiding an overload of options or simultaneous information, is essential so students can focus on tasks instead of getting lost in navigation. Prior training or interactive tutorials provide students with a solid foundation to familiarize themselves with the technology before facing more complex scenarios, thus reducing initial mental demand. The use of gamification turns cognitive tasks into more enjoyable and less overwhelming activities, increasing motivation and reducing the stress associated with challenging tasks. Additionally, facilitating navigation within the application ensures that students do not waste time or effort trying to find the necessary resources, reducing the mental load associated with orienting themselves within the virtual environment.

Finally, users should be asked for constant feedback, which will allow the application to be adjusted and improved according to the needs and capabilities of students. This iterative feedback ensures that the user experience remains effective and optimized, preventing the system from becoming a source of additional cognitive load. Together, these recommendations allow MR to be implemented effectively in the educational environment, offering an optimized and controlled learning experience that minimizes mental stress while maximizing pedagogical benefits.

6- Conclusions

The students who participated in the study perceived a low mental workload when interacting with the application, which is a key indicator of the tool's success. This finding suggests that Build_3D has achieved an appropriate balance between task complexity and interface usability, allowing students to focus on the essential aspects of learning without feeling overwhelmed by the technology.

From a pedagogical perspective, Build_3D has proven to be an effective tool for complementing the learning of complex topics such as hardware assembly, especially in areas where access to physical labs or real equipment may be limited. The ability to manipulate 3D models in an interactive environment has enhanced students' practical understanding, offering a deeper learning experience than traditional methods, such as textbooks or 2D simulations. The application, due to its ease of use, can be employed by both beginner and experienced students, demonstrating its versatility. However, despite the positive results, it is important to highlight the need to properly manage the usage periods of these technologies to avoid mental fatigue. Incorporating regular breaks is essential to ensure that students do not experience cognitive overload.

The implementation of Build_3D in educational environments has proven to be a promising solution for improving the comprehension and practical learning of PC and smartphone hardware. The low perceived mental workload and efficiency in task performance suggest that this technology can have a positive impact on teaching technical subjects, fostering greater motivation and knowledge retention among students.

Feedback from teachers who used the Build_3D application reinforces the effectiveness of MR in the educational environment. The teachers agreed that the use of Build_3D significantly improves practical learning by allowing students to repeat complex tasks, such as hardware assembly, in a safe and controlled environment. This offers a notable advantage over the physical limitations of traditional labs.

Another key aspect is Build_3D's ability to reduce cognitive load by breaking tasks into manageable modules and allowing students to progress at their own pace. This personalized learning approach facilitates the acquisition of necessary skills in a gradual and effective manner, regardless of the students' knowledge level. Moreover, the immersive and engaging nature of MR technology has proven to be a significant motivational factor, promoting autonomous learning and increasing student engagement with the content.

Overall, the research has not only demonstrated that Build_3D is an effective tool for learning PC and smartphone hardware but has also highlighted the crucial role of teachers in optimizing the use of this technology. Implementing these recommendations could potentially maximize the benefits of MR in higher education, promoting more practical, personalized, and motivating learning experiences.

6-1- Future Work

Based on the results obtained from this research, a long-term follow-up could be conducted to assess whether students using MR applications like Build_3D retain the acquired knowledge more effectively than those who learn through traditional methods. This would allow for measuring the real impact of MR on long-term memory and the transfer of skills to the real world. While this research focused on PC and smartphone hardware, it would be valuable to apply MR to other areas of study within computer science, engineering, and even other disciplines such as medicine or architecture. This could help identify which fields benefit the most from MR and which require specific adjustments in the implementation of the technology.

It is suggested that future researchers conduct a comparative study between different emerging technologies, such as mobile learning, artificial intelligence (AI), AR, VR, and MR, to provide insights into which tools are most effective for different types of educational tasks and whether there is an optimal combination of technologies to enhance learning outcomes in technical subjects. Furthermore, it would be interesting to analyze how MR can be adapted for students with disabilities or with limited access to technological resources. This could include the design of inclusive interfaces and the evaluation of how MR can be used to ensure that all students, regardless of physical abilities or resources, can benefit from immersive learning.

Additionally, the possibility of integrating Build_3D and other MR applications with continuous assessment systems that monitor students' progress in real-time could be explored. This would allow teachers to adjust the difficulty of tasks and provide personalized feedback based on each student's performance in an immersive environment.

These future research directions would not only expand knowledge on the application of MR in higher education but also provide new opportunities to optimize tools and improve students' learning experiences.

7- Declarations

7-1- Author Contributions

Conceptualization, S.C.-C., A.G.-A., and A.D.S.; methodology, S.C.-C. and A.G.-A.; software, S.C.-C.; validation, S.C.-C. and S.L.-M.; investigation, S.C.-C. and A.G.-A.; resources, S.C.-C. and A.G.-A.; data curation, S.C.-C., A.G.-A., and D.B-F.; writing—original draft preparation, S.C.-C. and A.G.-A.; writing—review and editing, S.C.-C., A.G.-A., and S.L.-M.; visualization, S.C.-C., A.D.S., and A.G.-A.; supervision, S.C.-C., A.G.-A., and S.L.-M.; project administration, S.C.-C. and A.G.-A. funding acquisition, S.C.-C. and D.B-F. All authors have read and agreed to the published version of the manuscript.

7-2- Data Availability Statement

The data presented in this study are openly available in Mendeley Data at Doi:10.17632/ftvmsf7z8b.1.

7-3- Funding

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7-4- Institutional Review Board Statement

Not applicable.

7-5- Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

7-6- Conflicts of Interest

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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