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Build_PC: Mobile Augmented Reality for Supporting PC Hardware Learning With Low Mental Workload

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ABSTRACT

The use of emerging technologies such as mobile augmented reality (MAR) in education has gained relevance, especially in technical areas such as PC hardware learning. However, a persistent problem is the cognitive load that these applications may impose on students, which could affect learning effectiveness and acceptance. This issue is crucial, as a high mental workload can lead to disengagement and lower knowledge retention. Previous studies have explored technological solutions for education but in many cases failed to optimize cognitive load or generate a satisfactory learning environment. This study proposes a MAR application called Build_PC, designed for hands-on teaching of PC hardware. The NASA-TLX tool was used to evaluate the mental workload in 60 students, analyzing dimensions such as mental, physical, temporal, performance, effort, and frustration level. The results show a low mental workload among students, suggesting that Build_PC achieves a balance between task complexity and interface usability. These findings have significant implications: The use of Build_PC in education enables effective, autonomous learning in a technologically advanced environment without imposing excessive mental workload. This supports MAR's potential as an effective and sustainable learning tool, particularly in contexts where access to physical laboratories is limited.

1 | Introduction

In recent years, immersive technologies such as augmented reality (AR) and virtual reality (VR) have revolutionized the educational field, opening new opportunities for hands-on learning and knowledge retention in various domains [1]. In particular, mobile augmented reality (MAR) has emerged as a promising tool for technical education, as it integrates virtual elements with the physical world, enabling more tangible and direct interactions with otherwise abstract concepts [2]. However, adopting these technologies in education presents significant challenges, particularly in managing the mental workload they may impose on students, especially in fields requiring high levels of concentration and technical understanding [3, 4].

Mental workload is a critical factor in designing educational experiences based on immersive technologies, as an excessive cognitive load can reduce academic performance, lower student motivation, and limit the tool's effectiveness [5]. In the educational context, in several subjects, students must acquire both theoretical and practical skills that foster engagement and motivate their learning [6]. Traditionally, this type of learning is conducted in equipped laboratories, which can be costly and difficult for many institutions to access [6, 7]. By providing an alternative to hands-on practice in physical laboratories, MAR technology has the potential to democratize access to this knowledge, but only if it is ensured that students can interact with the tool without experiencing high levels of cognitive load [8, 9].

Thus, the problem addressed by this research focuses on the creation of a technological solution that allows students to learn about computer hardware in a practical, interactive, and effective way, without compromising their cognitive well-being. PC hardware learning, in particular, faces the challenge of transmitting knowledge that requires not only theoretical understanding, but also practical skills that are difficult to acquire without an experiential component [10, 11]. This issue is of great importance, as achieving quality education is part of the Sustainable Development Goals (SDGs), which requires expanding digital education, including new methodologies that not only transmit knowledge, but are also accessible and student-friendly [12]. In this context, if the cognitive load is not properly managed, students may perceive this technological innovation as overly complex and discouraging, potentially reducing both its adoption and effectiveness [13–15].

MAR has become an innovative tool for transforming traditional education into interactive and personalized learning experiences [16]. Through devices such as smartphones and tablets, this technology integrates digital elements with the real environment, allowing students to explore abstract concepts in a visual and tactile way [17]. In this context, MAR not only facilitates understanding of complex content but also promotes motivation and engagement in learning [1, 18, 19].

MAR has found applications in a wide range of educational disciplines. In natural sciences, for example, students can interact with 3D models of human organs, planetary systems, or molecular structures, providing a deeper understanding than that offered by traditional textbooks [20–23]. In mathematics, applications such as GeoGebra AR enable real-time visualization and manipulation of three-dimensional graphs, improving spatial reasoning and problem-solving [24–26]. In humanities, MAR can transport students to digitally reconstructed historical scenarios, such as ancient cities or battlefields, enriching learning with an immersive perspective [27–29]. Similarly, in language learning, MAR applications integrate interactive exercises that combine object recognition and contextualized vocabulary, facilitating the acquisition of new languages [30–32].

The future of MAR in education is promising, with technological advancements making this technology more accessible and efficient. Applications leveraging MAR are evolving to incorporate artificial intelligence, enabling even more personalized and adaptive learning experiences [33]. For instance, systems are being designed to analyze student progress in real time and adjust activities according to their specific needs [34]. Furthermore, the integration of MAR with other emerging technologies, such as VR and mobile learning (m-learning), will open new possibilities for the design of immersive and collaborative educational experiences [16, 35]. These innovations could transform not only how it is delivered, but also its content, preparing students for an increasingly digitized and globalized world.

In this context, this research focuses on identifying how students perceive the cognitive demands and usability limitations within the specific context of Build_PC. The findings aim to provide initial evidence that can guide future, more comprehensive research. Based on these contextualized perceptions, the study contributes to improving the design and evaluation of learning management systems–based educational tools, supporting the development of more accessible, usable, and pedagogically aligned solutions that potentially enhance student participation and learning processes.

This section introduces the reader to how digital technologies have brought new opportunities to the field of education and how MAR technology can be used in current education. Section 2 outlines the literature review used to achieve the proposed objectives. Section 3 presents the method used to achieve the proposed objectives. Section 4 presents the study findings. Section 5 analyzes the results and suggests possible avenues for further research. Section 6 presents the conclusions.

2 | Literature Review

2.1 | Advantages and Challenges of Using MAR in Education

Among the main advantages of using MAR technology are interactivity and personalization of learning [36]. By engaging students in hands-on, exploratory activities, this technology fosters active, experience-based learning, leading to increased knowledge retention [37, 38]. MAR applications create immersive learning environments that significantly increase student engagement and interactivity [39]. This is achieved by overlaying virtual objects onto real-world environments, making learning more dynamic and interactive [40]. Additionally, since MAR is accessible from mobile devices, it democratizes access to innovative educational resources, overcoming the geographical and economic barriers that have traditionally limited access to educational technologies [22, 41].

MAR technology could adapt formal and informal learning experiences to the individual needs of learners [42]. This technology enables ubiquitous learning—anytime, anywhere—by taking advantage of the widespread availability of smartphones [43, 44]. MAR applications often include adjustable difficulty levels and real-time feedback, allowing learners to progress at their own pace and consolidate learning effectively [45]. This is particularly beneficial in inclusive educational contexts, where students with diverse abilities can fully participate in personalized educational activities [26, 46].

Although MAR offers numerous benefits, challenges related to usability and technical quality of the applications remain [47]. Designing and developing high-quality educational content using MAR technology requires a significant investment of time and resources [36]. Ensuring that MAR applications are user-friendly and technically robust is crucial for their effectiveness in educational environments [48]. To effectively integrate MAR into educational curricula, clear guidelines and pedagogical frameworks are required [43]. This includes understanding how to design MAR applications that align with learning theories and teaching strategies [49].

2.2 | MAR Applications in Hardware Learning

The use of digital technologies in education has demonstrated their ability to enrich teaching–learning processes, particularly in technical areas such as PC hardware [50]. Previous studies highlighted a variety of applications and prototypes designed to improve the understanding of complex concepts related to computer maintenance and internal structure.

Vasyl et al. [10] explored how AR applications allow students to observe the operation of computer systems by modifying their parameters. In addition, students were able to visualize algorithms, data processes, and modify hardware using AR, which facilitated interactive and hands-on understanding. The study highlighted AR's potential to enrich the emotional and cognitive experience, promoting collaborative and systematic learning.

Romero et al. [51] evaluated the virtual learning object (VLO) together with AR, designed to teach computer maintenance concepts related to the internal computer components. The results showed that VLO met the quality criteria, emphasizing aspects such as motivation, usability, and accessibility. However, it was suggested to complement the environment with a contextualized configuration adapted to the students' needs.

Fasihuddin [11] focused on addressing the limitations of traditional computer science teaching methods, especially in schools with limited budgets. A VR-based prototype was presented, providing an interactive learning environment for PC hardware. Functionality and usability test results were satisfactory, confirming the feasibility of enriching teaching methods in public schools with restricted resources.

Faizan et al. [52] evaluated an AR application focused on visualizing internal laptop components, such as SSD, HDD, RAM, CPU, GPU, and motherboards. The results indicated high levels of satisfaction in terms of interactivity, clarity of information, and ease of use, underscoring AR's effectiveness in creating intuitive and engaging educational experiences.

Sendari et al. [53] addressed the presentation of hardware components through AR, focusing on technical parameters, such as distance, detection angle, and lighting conditions. The results showed that the system performed adequately under various conditions, suggesting that AR is a viable tool for hardware learning.

Romero et al. [50] showed that an MAR technology application called "HardwareAR," not only facilitated students' understanding and motivation, but was also well received by educators. Every teacher considered it feasible to integrate it into classrooms for teaching internal PC components.

Previous research has shown that using AR and MAR in technical education offers benefits, such as increased knowledge retention and learner motivation [19, 25, 30]. However, in several cases, MAR applications tend to require many cognitive resources, either because of the complexity of the interface or the lack of an optimized design for progressive learning [37, 54]. Despite the progress made, few studies quantitatively assess the mental workload imposed by these types of environments, especially in MAR applications designed to reduce cognitive load and intended to support educational models. This gap highlights the need to analyze the cognitive efficiency of these tools and their impact on user experience.

2.3 | Cognitive Load and Mental Load

The terms "cognitive load" and "mental load" may seem synonymous, but they do not mean the same thing, although they are closely related [55]. The main difference lies in their theoretical approach and how they are measured or interpreted in learning or human–computer interaction contexts [56].

Cognitive load is based on cognitive load theory (CLT), proposed by Sweller in 1988 [57], which explains how instructional design and information organization affect learning efficiency. From this perspective, cognitive load is classified into three types: intrinsic, derived from the inherent complexity of the content; extrinsic, associated with inadequate design or irrelevant stimuli; and adhering, related to the mental effort that contributes to the construction of meaningful schemas. Thus, the concept of cognitive load is oriented toward understanding the cognitive processes involved in the acquisition and retention of knowledge [58].

Mental load stems from cognitive ergonomics and the study of human workload, particularly in applied psychology and human–computer interaction [55]. Unlike the educational approach to CLT, mental load is assessed using psychometric instruments, such as the NASA Task Load Index (NASA-TLX) [59], which considers six dimensions: mental demand, physical demand, time demand, effort, perceived performance, and frustration. This approach does not aim to explain how learning occurs, but rather how much effort an individual perceives during interaction with a technological system or environment.

In this research, a mobile application called Build_PC was developed, which, unlike previous approaches, aims to optimize the user's cognitive load by applying design principles centered on the three phases of CLT [60, 61]. The application allows students to visualize, manipulate, and assemble PC components in a safe and controlled environment, without the need for physical equipment, thus facilitating learning and minimizing cognitive load thanks to an intuitive and simplified interface.

2.4 | Synthesis and Research Gap

The reviewed literature indicates that MAR (multimedia applications) can improve learning in technical areas such as PC hardware by fostering interactivity and the understanding of complex content. However, several studies warn that these applications can generate high levels of mental workload, effort, and frustration due to limitations in interface design and information organization.

Despite this background, there is limited empirical evidence that systematically analyzes the mental, physical, and temporal demands experienced by students when using MAR applications in educational contexts, especially through standardized instruments such as the NASA-TLX. Furthermore, few studies use these results to propose concrete improvements aimed at optimizing the design and ensuring the proper integration of MAR into educational models.

In response to this gap, the present research evaluates the Build_PC application in order to analyze the mental load, effort, frustration, and physical and temporal demands perceived by students, and to derive design recommendations based on the results of NASA-TLX that contribute to an effective integration of MAR as an educational support tool.

Thus, the objectives of this study are directly derived from the limitations identified in the literature, providing empirical evidence on the optimization of mental workload in immersive and mobile learning environments. The objectives of this research are as follows:

- Objective 1: To what extent do students experience frustration, effort, and mental, physical, and time-related demands when using the Build_PC application, and can it be effectively used as a support tool in education?
- Objective 2: How do the results of the NASA-TLX survey inform improvements in the design of MAR applications for effective integration into educational settings?

3 | Methodology

This study is part of an ongoing research project focused on analyzing the educational potential of MAR applications for teaching technology content. Previous research by the authors has explored various complementary approaches using the Build_PC application and associated assessment tools. One earlier study explored usability and technological adoption in international contexts to understand the user experience and the feasibility of implementation in different educational settings [62]. Another study analyzed the application's impact on academic performance using experimental designs with control and experimental groups, focusing on learning outcomes and pedagogical effectiveness [2]. In parallel, independent research has employed instruments such as NASA-TLX in different educational applications for methodological purposes related to assessing mental workload in interactive environments [3].

To evaluate the effectiveness of Build_PC in terms of mental workload, this study employs the NASA-TLX tool [59]. A sample of 60 students was used, who used the application and completed a survey. This survey was validated to determine the impact of Build_PC on six dimensions (mental, physical, temporal, performance, effort, and frustration) and to verify whether it maintains mental workload at levels suitable for effective learning [5]. The selected students were enrolled in an engineering program and had basic knowledge of computer hardware, ensuring content relevance and allowing for an objective assessment in a realistic educational context.

In this context, this section details the methodological processes employed, starting with the development of the application, which included the definition of requirements, the selection of technologies, and the implementation of an interactive environment capable of simulating PC hardware configurations and component assemblies. Subsequently, the application of this tool in an educational context is addressed, evaluating its impact on the perception of students' mental workload, using the NASA-TLX survey. This comprehensive methodological approach allowed validating the functionality of Build_PC, as well as its effectiveness in reducing cognitive and physical demands during the learning process.

Unlike previous AR applications that focus on visualization or student motivation, Build_PC was conceived under the principles of CLT, with the explicit purpose of minimizing extrinsic load, managing intrinsic load, and enhancing cognitive load during virtual hardware assembly practice.

To reduce the intrinsic workload, BUILD_3D applies the following principles:

- Segmentation: Students complete the assembly in several sequential and manageable steps, avoiding overwhelming them with too much information simultaneously.
- Progression of difficulty: Students begin with basic tasks (installing RAM, identifying components) and progress to more complex tasks (installing the CPU, cable management).
- Pace control: The user controls the pace, allowing them to manage their own level of cognitive effort.

To reduce extrinsic load, BUILD_3D incorporates the following:

- Coherence principle: The interface eliminates distracting elements, unnecessary animations, and superfluous sounds.
- Signal: Visual indicators, arrows, highlighted parts, and colors are used to direct attention to relevant elements.
- Spatial and temporal contiguity: Instructions, 3D models, and required actions appear integrated within the same visual field, preventing the student from scattering their attention among multiple sources.
- Minimizing the split-attention effect: Instructions are superimposed next to the real/virtual 3D object without forcing the user to switch between manuals or external screens.

To minimize the German cost, Build_PC uses the following principles:

- Immediate feedback: The system indicates whether the piece was placed correctly and offers additional guidance for correcting errors.
- Manipulable 3D representations: The student can rotate, zoom, and manipulate the components in a 3D environment, strengthening spatial and procedural understanding.
- Active interaction: The model promotes the active construction of knowledge through virtual assembly, in line with experiential learning.
- Personalization principle: The system uses user-friendly and direct language in its instructions, which improves cognitive processing.

Furthermore, Build_PC stands out for its mobile implementation, designed to operate without the need for headsets or high-end equipment, making it viable in educational contexts with limited resources. Its interface is structured according to principles of coherence, contiguity, and cognitive segmentation, allowing students to learn gradually and autonomously.

3.1 | MAR Application Design

The design process of a MAR application enables the seamless integration of digital elements with the real environment, ensuring that the information presented is relevant and accessible to the user. Through a user-centered design approach, usability issues can be identified and resolved, resulting in an interactive and engaging experience that encourages engagement in learning. Below is a detail of how the key components were identified to facilitate interaction and learning through AR technology.

Initially, the main components of a desktop computer and their respective functions were identified. Subsequently, the capabilities of mobile devices with the Android operating system were investigated to determine the tools and software development kits suitable for developing the educational application. Finally, frameworks and libraries used in Unity for developing MAR applications were classified. These libraries needed to facilitate the tracking of a 2D physical model and map the desktop computer model to the real world through the mobile device's camera. The chosen framework was Vuforia 11.4, a licensed system that provides AR capabilities without consuming excessive resources.

For the computer model, a free asset downloaded from the internet was used, which was later optimized for seamless use on mobile devices [63]. The open-source tool Blender 3.6 LTS was utilized for this purpose. The number of interfaces to be displayed to users was defined, including the settings menu and the information window for the desktop computer components. Subsequently, the positioning and style of elements in each interface were designed, including text placement, color, size, and font type.

Several interaction possibilities were defined, such as using cursors, interacting through the camera with hand gestures, among others. Ultimately, a raycasting system was chosen to allow users to tap on a component on the screen, with the application responsible for mapping that point and component to the exact location within the computer case.

3.1.1 | Design Elements

The development of the marker-based MAR application called Build_PC was carried out using Unity 2022.3.17f1 LTS together with Visual Studio 2022 Community Edition. These are commonly used tools in the development of AR video games. The features of these platforms are explained in Table 1. The following libraries were used for application development:

- Unity (UnityEngine/UnityEngine.UI): for connecting and using Unity engine's internal functions.
- UnityEngine.InputSystem: for user interaction with the application and UI.
- Vuforia: to use the phone's camera and have a model to track the PC.

In the development of an application, which is going to be used as support in education, it is essential to clearly and precisely establish the requirements and needs that are intended to be addressed [64, 65]. These elements will guide the creative process, ensuring that the application is effective in meeting its educational objectives [64]. Likewise, the design must ensure that the application motivates users and encourages them to use it [66, 67]. Therefore, it should have a user-friendly interface, be simple, coherent, and intuitive, avoiding redundancy and offering interactive navigation [64, 65, 68, 69]. In this case, the requirements were identified in a previous study [61] and are listed in Table 2. Additionally, due to the specific design and usability, Build_PC has the following functionalities:

- Component Interaction: The user should be able to interact with the PC components and interface freely, easily, and intuitively.
- Component Information: The user should be able to obtain information about each component and its function.
- Component Order Verification: The user should receive feedback when making an error. Visualization: The user should be able to see the PC components clearly and without confusion, both inside and outside the case.
- Friendly Environment: The user should perceive an environment where they can work and complete the proposed exercises without problems.

The configuration of these activities was carried out within a set timeframe defined in Table 3. If problems arose, the team would briefly meet to resolve doubts and continue with the project. The priority of each cycle was determined by the project's final objectives. At the end of each cycle, the work done was reviewed, demonstrated, and adapted in a team meeting to finalize Build_PC development. The following are images of the designed application's use. Figure 1 shows how Build_PC places PC elements in 3D on the mobile device screen. Furthermore, it is important to note that the 3D image is generated using a marker, which can also be seen in the image.

3.1.2 | Build_PC Operation

The Build_PC design incorporates a language-switching feature. Users can choose to view interface information in four languages.

TABLE 1 | Platforms used in the development of Build_PC.

Development platforms	Features
Unity 2022.3.17f1 LTS	Unity is a video game development platform that has different versions of long-term support (LTS). Also, it can be defined as a game engine that provides a complete environment for the development of 2D and 3D video games, as well as mixed reality (XR). The developed games can be exported for use in different devices, such as desktop computers, laptops, consoles, smartphones, tablets, and Oculus, among others
Visual Studio 2022	Visual Studio is an integrated development environment (IDE) produced by Microsoft. This software is used to write, debug, and compile programming code. It includes a package that can be installed to connect to Unity and debug code while running the application

TABLE 2 | General requirements for the design of MAR applications [60, 61].

Requirements	Features
Simple and easy to use	Provide ease of use of the application, so the user can use the application without any major difficulties
Consistent interfaces	Use known functionalities that resemble computer menus
Nice design	Generate satisfaction, enthusiasm, and fun by using the different controls in the activities carried out by the application
Feedback	Provide an understanding of mistakes made to improve task interpretation
Multimedia content	Generate use intent by creating multimedia interfaces that attract the user's attention
Intuition	Avoid user disorientation due to the total number of interactions
Motivation	Motivate the user with kind messages while progressing through the game
Navigability	Follow the user interface design principles established by the platform on which the mobile application was developed
Lightweight	The application must allow its execution on devices with limited processing and storage capacity, although this results in a loss of performance
Extensibility	The sensors of a device are different depending on the hardware used by the manufacturers. With the wide variety of methods for obtaining information, the designed application must be open to new ways of accessing the sensors
Ease of testing and maintenance	Consistency in components should facilitate the development of unit tests and the maintenance of the application

TABLE 3 | Iterations required for the construction of the MAR application.

Iteration number	Definition	Priority (1–10)	Iteration duration (weeks)
1	Create components	10	1
2	Create interaction	10	1
3	Optimize models	6	2
4	Create tracking model	9	1
5	Create UI elements	8	1
6	Create block order verification	6	1
7	Create option not to use tracking	9	2
8	Add component information	9	1
9	Create saving system	7	2
10	Create object thumbnails for the information screen	5	1
	Total duration of mobile application development		13 weeks

This multilingual capability enables Build_PC to cater to a diverse audience, accommodating various linguistic preferences. By supporting multiple languages, the application enhances accessibility and inclusion, thereby broadening its educational reach and impact. This feature ensures that users from different linguistic backgrounds can effectively engage with the application, further supporting its goal of providing a comprehensive and user-centric educational tool. Moreover, the inclusion of a language-switching feature demonstrates a commitment to global usability and user satisfaction, contributing to a more inclusive educational experience. The design approach not only addresses immediate user needs but also anticipates future demands for expanded language support, thus aligning with best practices in educational technology development.

Furthermore, Build_3D aligns with contemporary AR instructional design guidelines according to [56, 70]. The architecture of Build_PC, which overlays virtual computer components onto a real-world environment, aligns with the spatiality and contextuality dimensions described by Gonnerman-Müller et al. [56]. Moreover, the design of Build_PC can be analyzed in terms of the principles of spatial contiguity and coherence described by Krüger et al. [70]. This ensures that related textual and graphical information appears within the same visual field, thus reducing extrinsic cognitive processing. Overall, Build_PC represents a new generation of educational tools based on MAR, characterized by its pedagogical orientation, empirical validation of low cognitive effort, and viability as a partial substitute for the physical laboratory. This approach distinguishes it from previous developments focused solely on

FIGURE 1 | Build_PC in operation, 3D elements are displayed over the real image captured by the mobile phone camera.

technological demonstration, establishing it as an example of efficient, accessible, and cognitively sustainable learning. Figure 2 shows the elements and information with which students can interact when using Build_PC. It can be observed that the elements are in a very light color, except for the selected element from which all the information is obtained.

3.2 | Research Design

An experimental design was employed to evaluate the mental workload experienced by students when using the Build_PC as a support tool for learning PC hardware. This approach allowed observing the influence of MAR technology on educational experience, focusing on the perception of mental workload through the NASA-TLX survey [5]. The intervention lasted approximately 25–30 min, distributed in guided assembly and diagnosis activities of PC components.

3.2.1 | Participants

The sample consisted of 60 students, of whom 51 were male and 9 were female students (85% male and 15% female). The gender gap in engineering careers, as observed in the sample, responds to social stereotypes, a lack of female referents, and noninclusive environments. These cultural and educational barriers limit the interest and participation of women in STEM areas, reflecting the need to promote greater equity and inclusion.

Participants were selected by nonprobabilistic sampling based on availability, prioritizing those enrolled in subjects related to technology and computer science. Informed consent was obtained from each student, ensuring anonymity and confidentiality of the data collected.

3.2.2 | Ethical Considerations

The integrity of the participants was ensured by obtaining informed consent and implementing measures that guarantee confidentiality of the information. In addition, participants could leave the experiment at any time. The research had the approval of faculty management, complying with the ethical and regulatory standards established for research in educational settings.

3.2.3 | Instruments

Two main instruments were used in this research:

- Build_PC application: A MAR application designed to facilitate interactive learning about PC hardware. The tool allows users to visualize and manipulate computer components in an AR environment and simulate assemblies, offering immersive and practical experience.
- NASA-TLX survey: To evaluate workload, the NASA-TLX survey was applied, which measures the perception of effort and demand in six dimensions: mental, physical, temporal, performance, effort, and frustration. This tool is detailed in Table 4. This instrument was chosen due to its well-established use in the measurement of workload in complex environments [59].

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3.2.4 | Procedure

The procedure consists of three steps:

A. Explaining: The study began with an introductory session explaining the operation of the "Build_PC" application and presenting the purpose of the research. Students were given hands-on training to ensure proper handling of the tool, which minimized possible technical difficulties during interaction with the application.

B. Activity Implementation: The students carried out a series of interactive activities using the application. During these sessions, participants explored different modules related to

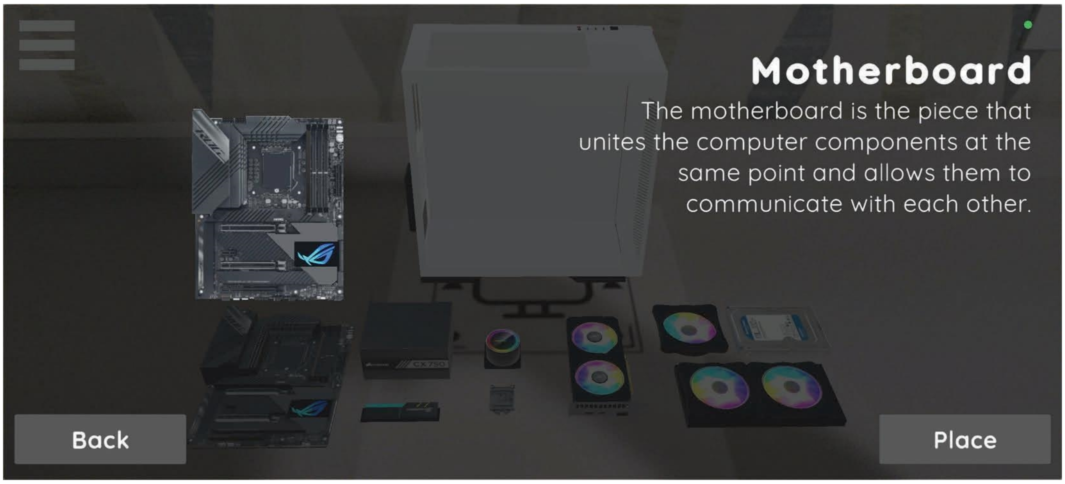

FIGURE 2 | On-screen information about the characteristics of the Build_PC elements.

TABLE 4 | NASA-TLX rating dimension description [5].

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

PC hardware, performed assembly simulations, and conducted diagnostics, thus allowing for a hands-on and enriching experience.

C. Data Collection: Upon conclusion of the activity, the NASA-TLX survey was administered on an individual basis. Participants evaluated their perception of frustration, effort, and temporal, mental, and physical demands experienced during the use of the application. Data obtained from the survey were subjected to quantitative analysis. Descriptive statistical techniques were applied to characterize the workload experienced, and analytical tests were performed to contrast the levels of load in relation to the use of the application.

4 | Results

This section presents the findings obtained after the implementation of Build_PC and the application of the NASA-TLX survey to assess the workload during the learning process of PC hardware.

The perceptions of the 60 participants regarding the mental, physical, and temporal demands, as well as the level of effort and frustration experienced during the interaction with the AR technology, were analyzed. From the data collected, significant trends and differences were identified, allowing for an evaluation of the application's impact on the learning process and formulation of recommendations for the optimal deployment of similar tools in educational settings.

The results demonstrate a generally low workload when using Build_PC as a support tool for teaching PC hardware. Table 5 and Figures 3 and 4 show the NASA-TLX survey values of the evaluated students.

Here, it can be seen that the MD, with an average of 7.10, shows that the task involved a significant cognitive demand. This suggests that students had to actively concentrate, think, and process information. The PD has an average of 1.00 (and in all the cases reported as 1), which means that the evaluated activity required almost no physical effort, indicating a minimal bodily demand. TD has an average of 2.22, in the range of 1–4,

TABLE 5 | Average and standard deviation of NASA-TLX responses (Scale 1–20).

Students	MD	PD	TD	PE	EF	FL
Average	7.10	1.00	2.22	14.30	2.37	2.22
Standard deviation	1.15	0.00	0.97	2.49	1.08	0.97

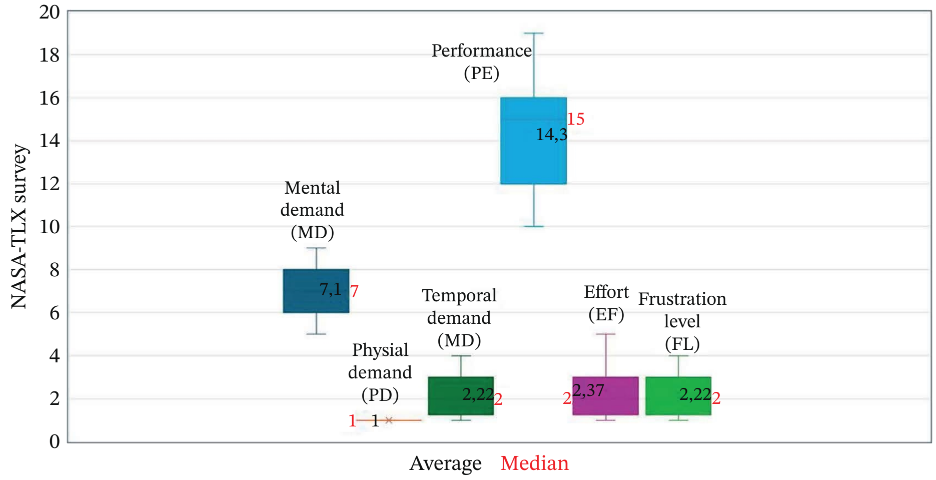

FIGURE 3 | Average and median of the responses for the six dimensions of the NASA-TLX.

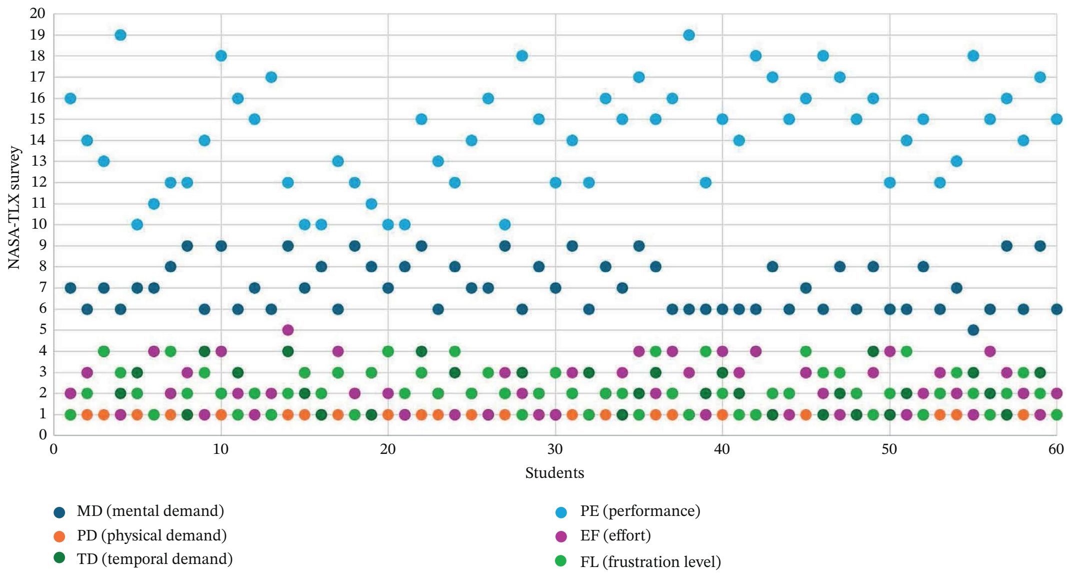

FIGURE 4 | Answers to the six dimensions of NASA-TLX.

suggesting that, in general, participants did not feel excessively pressured by the time or speed at which they had to perform the task.

In this context, the PE shows a value of 14.30 on average (range 10–19), which seems to indicate that most participants felt relatively satisfied with their performance. The EF has an average of 2.37, in a range of 1–5, reflecting a mild to moderate level of perceived effort. This fits with the fact that the task is mentally demanding but not excessive in other factors (time, frustration, etc.).

Finally, the FL shows an average of 2.22, also in a range of 1–4. This indicates that overall frustration was moderate; some participants may have felt some tension or discomfort, but it was not high overall.

Table 6 presents a comparison between NASA-TLX dimensions, and the columns correspond to each pair of dimensions (e.g., MD–PD, MD–EF, etc.). The rows indicate how many times each dimension was rated as more important than the other. Since there are 60 participants and each one makes 15 comparisons (one for each pair among the 6 dimensions), in total, there are $60 \times 15 = 900$ distributed votes. For example, in the MD–PD column, the MD row shows 60 and the PD row shows 0. This means that in the MD vs PD comparison, all 60 participants chose MD as more important than PD. In this context, it can be indicated that all

TABLE 6 | NASA-TLX dimension pair analysis.

Students	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	Total
Mental demand (MD)	9	43	58	32	6	—	—	—	—	—	—	—	—	—	—	**199**
Physical demand (PD)	—	—	—	—	—	33	22	8	—	15	—	—	—	—	—	**78**
Temporal demand (TD)	—	—	—	—	54	—	—	52	13	—	—	—	—	46	48	**213**
Performance (PE)	—	—	—	28	—	—	38	—	47	—	—	54	45	—	—	**212**
Effort (EF)	—	17	—	—	—	—	—	—	—	45	49	—	15	—	12	**138**
Frustration level (FL)	—	—	2	—	—	27	—	—	—	—	11	6	—	14	—	**60**

Note: The total values represent the number of times each dimension was selected as most influential in the comparisons made. In other words, they indicate the relative weight of each dimension in the workload perceived by the students.

participants estimate MD to be more significant than PD, which is consistent with the idea that the task requires almost no physical effort and, instead, significant cognitive processing.

Virtually all participants consider MD more important than LF, suggesting that even if some LF exists, it is not seen as a main factor defining workload compared to cognitive workload. In this context, although MD obtained high values in the rating, when directly compared to TD, most participants (54) consider that time influences their perception of workload more than the mental demand itself. This result shows the great importance of deadlines or time pressure in the experience of the overall load. When adding up their comparisons, PE accumulates 212 votes, placing it very close to TD (213). Furthermore, in PE vs TD, the majority (47) choose PE; in contrast, in MD vs TD, the majority (54) choose TD. This reflects the variability in how each person prioritizes time pressure or perceived performance depending on the point of comparison. In this context, EF is perceived to be more relevant than PD, but less so than MD and TD. The EF was in the moderate range, indicating that, although students perceived cognitive or general effort, it was not extreme.

Finally, the FL is characterized by being low in the overall evaluation, which is a positive indication for the user experience. All these results contrast with Figure 5, where it can be seen graphically that the mental workload perceived by the students is low, with certain values at the medium level, but far from a high mental workload.

Subsequently, with the help of these data, the mental workload was calculated using the NASA-TLX tool. Tables 7 and 8 present the responses of student number one. With these data, an example of the quantitative calculation of the mental load perceived by this participant is made. Table 9 shows that in Column A, the weight of MD, PD, TD, PE, EF, and FL is placed, which represents how many times these dimensions are repeated in Table 7. Column B shows the score obtained in MD, PD, TD, PE, EF, and FL in Table 8. Columns C and D respond to a simple formula between the columns: $B \times 5$ and $C \times A$. The total quantitative score, which defines the students' perception of the mental load when using Build_PC, was 495 points. This value, according to Table 10, indicates that student one perceives a low mental load when using Build_PC. Table 10 presents the total result of the level of mental load perceived by the students who participated in this research. There are 46 students (76.67%) who perceive a low level of mental load when using the application. On the other hand, the remaining 14 students (23.33%) perceive a medium level of mental workload when using the application. It is important to note that there are no students who perceive a high level of mental workload associated with using Build_PC. Therefore, it can be concluded that most students perceive a low level of mental load when using Build_PC. Figure 5 illustrates the students' responses, and these are concentrated in the values between 265 and 605. This indicates that students did not experience an excessive mental load when using the application as support in teaching PC hardware.

5 | Discussion

5.1 | Cognitive Demands and Educational Viability of Build_PC as an Educational Support Tool

The central purpose of this research was to analyze whether students experience levels of frustration, effort, and various

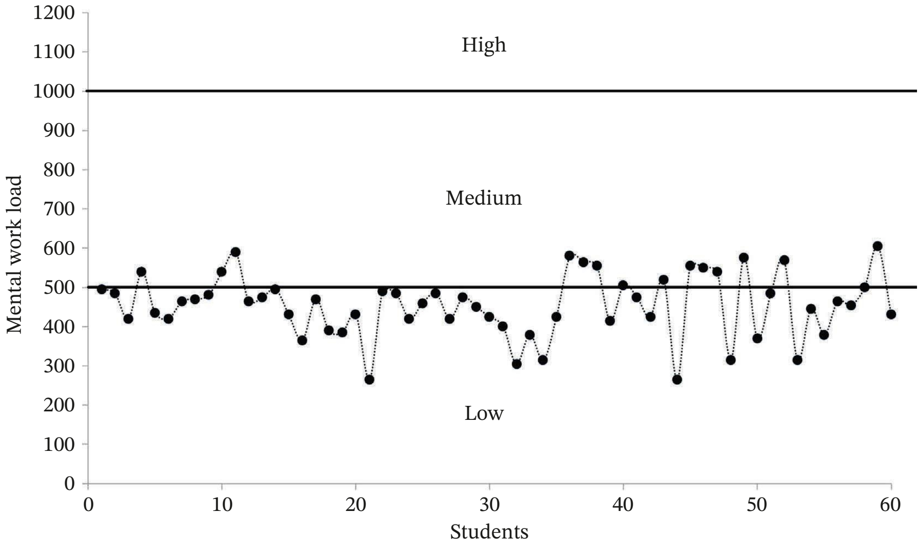

FIGURE 5 | Responses of the 60 participants to the NASA-TLX survey.

demands (temporal, mental, and physical) when using the Build_PC application as educational support. The results show a high rating of mental demand (average of 7.10), indicating that the task assessed requires considerable cognitive processing. This is consistent with the nature of the application, as assembling or interacting in MAR environments requires concentration, analysis, and decision making. The high mental demand is contrasted with the low physical demand, evidence that the main challenge is cognitive.

The fact that PD has a constant value (average of 1.00) confirms that the application does not require significant physical effort. This is to be expected in a digital environment where the use of the MAR focuses on virtual interaction, allowing students to concentrate on the content and the learning process without distractions from physical demands.

The average TD (2.22) and the high number of votes in its comparison (especially against MD) indicate that time pressure is perceived as important. Many participants identified time management and urgency to complete tasks as relevant factors in workload. This finding suggests that, although the task is primarily mental, the time component may increase stress at certain times.

EF is at moderate levels (average of 2.37). Although students recognize that the task requires a significant investment of cognitive resources, this effort is not excessive. In the weighting, effort ranks behind TD and MD, reinforcing the idea that students feel capable of coping with the activity, even though they recognize a considerable challenge.

The FL dimension presents a low average (2.22) and, in the pairwise comparisons, frustration never turns out to be the most decisive dimension in the overall load. This low level of FL is a positive indicator, as it suggests that, despite the high MD, the application is designed in such a way as to minimize negative emotions that may affect student motivation or engagement.

The results in PE (average of 14.30) indicate that students self-assessed their performance positively. This reinforces the validity of the application as an educational tool, as high perceived performance is associated with a successful user experience and a sense of having met the stated objectives, despite the cognitive and temporal demands.

The literature review on MAR technology applications suggests that these tools have the potential to improve interaction, increase motivation, and facilitate the understanding of complex concepts through an immersive experience. However, previous studies have also warned that information overload and time pressure can negatively affect the learning experience if not properly managed.

In this regard, the results obtained in Build_PC confirm previous findings: high MD is inherent to the use of educational AR environments, but this workload can be balanced through proper interface design and activity structuring. The low LF and moderate level of effort indicate that, while challenges are recognized, the overall experience is positive, and students feel competent in their execution.

In this context, the workload assessment findings are combined to support the feasibility of Build_PC as an educational tool based on MAR. Some key aspects include a high perception of performance, as students self-assessed themselves with high performance scores, indicating that, despite facing high mental requirements and sometimes pressure, they manage to meet the learning objectives and feel competent during the activity. In addition, the absence of high levels of frustration is crucial to the success of any educational tool. MAR technology, by facilitating an immersive and dynamic environment, can motivate students and promote active learning without generating a negative emotional experience.

In this scenario, moderate perceived effort suggests that the application challenges students enough to keep them engaged, but without becoming saturated. This is essential to foster knowledge retention and for technology to be effectively integrated into the educational process. The high mental demand observed is inherent in the use of AR environments, where interaction with virtual elements requires concentration and information processing. While this poses a challenge, it also indicates that the application is able to engage students in

TABLE 7 | NASA-TLX dimension pair analysis (Student 1).

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	MD	MD	PE	TD	PD	PD	TD	PE	EF	EF	PE	PE	TD	TD

complex activities, which can be beneficial for learning advanced concepts.

5.2 | Design Implications for Optimizing MAR Applications in Education

Based on the analysis of the dimensions evaluated through the NASA-TLX instrument and in line with the reviewed literature, several design implications can be derived to optimize the use of MAR applications in educational contexts. These implications should be understood as interconnected strategies that support a cognitively sustainable and pedagogically effective learning experience.

First, the results highlight the importance of appropriately managing perceived temporal demand. Although physical demand and frustration levels were low, time pressure emerged as a relevant factor in students' workload perception. Allowing pauses during activities, adjusting task pacing, and providing temporal cues can help reduce feelings of urgency, enabling learners to engage with the content in a more controlled and reflective manner.

Task segmentation also emerges as a key strategy for mitigating mental demand in complex learning activities. Dividing learning tasks into clearly defined stages allows students to focus on specific objectives, facilitates self-regulation, and reinforces a sense of progressive achievement. This approach is particularly relevant in MAR environments, where interaction with virtual elements inherently requires sustained cognitive processing.

Another important implication concerns the optimization of mental load through contextual support. The integration of interactive tutorials, contextual hints, and on-demand guidance can reduce uncertainty and the need for excessive autonomous information processing. Such design features help minimize extraneous cognitive load while preserving the instructional challenge of the activity.

Interface design plays a central role in shaping the user experience. Visually simplified interfaces, with well-organized and hierarchically structured elements, contribute to reducing unnecessary cognitive effort and support learners' attention on core learning objectives. In this regard, clarity, consistency, and the avoidance of distracting visual elements are essential design principles for MAR-based educational tools.

Furthermore, providing immediate and meaningful feedback is critical for sustaining motivation and engagement. Progress indicators, achievement recognition, and constructive feedback enable students to monitor their performance in real time, strengthen their sense of competence, and prevent frustration during task execution.

Finally, clearly defined objectives and evaluation criteria, combined with interactive support mechanisms and moderate gamification elements, can enhance the integration of MAR applications into formal educational models. These strategies foster positive emotional experiences, encourage active participation, and support long-term engagement without imposing additional mental workload.

Taken together, these design implications, directly derived from the analysis of perceived workload, offer practical guidance for the development and effective integration of MAR applications as

TABLE 8 | NASA-TLX dimension (Student 1).

MD	PD	TD	PE	EF	FL
7	1	2	16	2	1

TABLE 9 | NASA-TLX evaluation (Student 1).

Dimension	A. Weight	B. Score	C. Converted score (B × 5)	D. Weighted score (C × A)
MD	3	7	35	105
PD	2	1	5	10
TD	4	2	10	40
PE	4	16	80	320
EF	2	2	10	20
FL	0	1	5	0
Total	0	29	145	495

TABLE 10 | NASA-TLX scoreboard.

NASA-TLX	Mental workload level
Score less than or equal to 500 points	46 students (Low)
Score greater than 500 points and less than 1000 points	14 students (Medium)
Score over 1000 points	0 (High)

educational support tools. By balancing cognitive challenge, usability, and learner experience, MAR environments can be sustainably incorporated into educational practice.

5.3 | Limitations and Future Research Directions

While the findings of this study provide evidence supporting the feasibility of Build_PC as a MAR educational tool with a manageable mental workload, several limitations should be acknowledged to enable a balanced interpretation of the results and to inform future research.

First, the study was conducted with a relatively homogeneous sample drawn from a specific educational context. Although the results indicate low levels of perceived workload and high self-perceived performance, the generalizability of these findings may be limited. Future research should involve larger and more diverse populations, including students from different age groups, educational levels, and cultural backgrounds, in order to validate the robustness and transferability of the results across varied learning contexts.

Second, the evaluation focused primarily on subjective workload perception using the NASA-TLX. While this instrument provides a well-established ergonomic assessment of mental, physical, and temporal demands, effort, performance, and frustration, it does not explicitly account for the instructional mechanisms underlying learning. Future studies should therefore integrate instruments grounded in CLT to distinguish between intrinsic, extraneous, and germane cognitive load. Combining CLT-based measures with NASA-TLX would enable a more comprehensive analysis that captures both perceived workload and theoretically grounded learning processes.

Third, the present study did not include an experimental or quasiexperimental comparison with traditional instructional methods or alternative digital learning tools. As a result, the conclusions are limited to the evaluation of Build_PC in isolation. Future research should adopt comparative designs to assess differences in workload, usability, learning outcomes, knowledge retention, and task completion time between MAR-based environments and conventional instructional approaches. Such designs would strengthen causal inferences regarding the educational effectiveness of MAR applications.

Additionally, reliance on self-reported measures represents another limitation. Although subjective perception is a critical component of user experience, future research could incorporate objective indicators of cognitive effort, such as eye-tracking data, physiological measures, or interaction logs. These complementary data sources would allow for triangulation and provide deeper insights into how learners allocate attention and cognitive resources while interacting with MAR environments.

Addressing these limitations through extended empirical designs will contribute to the development of cognitively optimized and pedagogically grounded MAR applications. By integrating subjective, objective, and theory-driven measures, future research can advance the systematic evaluation and design of MAR-based learning environments that enhance learning efficiency, engagement, and sustainability in technical education.

6 | Conclusions

The current study differs conceptually by focusing specifically on the detailed evaluation of perceived mental workload during the use of Build_PC and on deriving design implications for optimizing MAR applications in education. Therefore, although it shares technological and methodological continuity with previous research within the same scientific line, it presents original objectives, research questions, analyses, and contributions aimed at understanding the cognitive sustainability of immersive learning environments.

This study proposed and evaluated Build_PC, a MAR application designed to support PC hardware learning while maintaining a low mental workload. Grounded in CLT and developed following user-centered design principles, Build_PC was conceived not only as a technological innovation, but as a pedagogically oriented tool aimed at minimizing extraneous cognitive load, managing intrinsic load, and fostering germane processing in technical education contexts.

Regarding Objective 1, the findings based on the NASA-TLX instrument show that students experience an overall low to medium level of mental workload when using Build_PC. Specifically, most participants (76.67%) perceived a low workload and none of them reported high workload levels. Mental demand was rated as high, which is consistent with the cognitively demanding nature of PC hardware assembly tasks and reflects active engagement in processing technical information. However, this mental demand was accompanied by very low physical and temporal demands, moderate effort, and low frustration, together with high self-perceived performance. These results indicate that Build_PC successfully balances challenge and usability, allowing students to focus on meaningful learning without experiencing cognitive overload or negative emotional reactions.

In relation to Objective 2, the analysis of NASA-TLX dimensions enabled the formulation of concrete design recommendations for MAR-based educational tools. The results highlight the importance of managing time pressure, segmenting tasks into manageable stages, providing clear goals and immediate feedback, and simplifying the interface to avoid unnecessary visual or interactive complexity. These recommendations contribute to the design of MAR applications that are not only engaging and motivating, but also cognitively sustainable, facilitating their integration into curricula as effective support tools rather than as occasional demonstrations.

Taken together, the results position Build_PC as a feasible and scalable alternative to traditional laboratory-based instruction for PC hardware, especially in institutions with limited access to physical equipment. Its mobile implementation, lightweight architecture, and multilingual interface enhance accessibility and broaden its potential impact across diverse educational contexts. Furthermore, by combining CLT-based design with a quantitative assessment of mental workload, this research advances the understanding of how MAR applications can be systematically evaluated and optimized from both pedagogical and ergonomic perspectives.

The main innovative features of this research include the following:

- Mental Load Assessment: The NASA-TLX tool is used to measure dimensions such as mental, physical, and temporal demand, as well as effort, performance, and frustration levels in 60 students.
- Balance between Complexity and Usability: The results demonstrate a low mental workload, indicating that the application successfully balances task complexity with ease of use.
- Effective Learning Environment: Build_PC enables interactive exploration of hardware components, complementing theoretical and practical learning in an accessible, autonomous format.
- Adaptability: The application is designed for educational contexts with limited resources, offering a viable alternative to physical laboratories.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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