Journal on Interactive Systems, 2026, 17:1
ISSN: 2763-7719 • doi: 10.5753/jis.2026.5755

RESEARCH PAPER

Innovations in Geometry Teaching with MiritiBoard VR 2.0 Glasses: Customizations and Usability Evaluation

João Francisco Moreira de Carvalho [Federal University of Pará | *joaofran.m.c@gmail.com*]
Flávio Rafael Trindade Moura [Federal University of Pará | *flavio.moura@itec.ufpa.br*]
Lucas Gabriel do Carmo Pereira [Federal University of Pará | *luccasg.pereira@gmail.com*]
Leonardo da Conceição Estevam [Federal University of Pará | *leonardoestevam0605@gmail.com*]
Waldemiro José Assis Gomes Negreiros [Federal Institute of Pará | *waldemiro.negreiros@ifpa.edu.br*]
André Vinícius Neves Alves [Federal University of Pará | *andre.neves.alves@itec.ufpa.br*]
Lyanh Vinicios Lopes Pinto [Federal University of Pará | *lyanh.pinto@itec.ufpa.br*]
André Jordan Santos dos Santos [Federal University of Pará | *andre.santos@itec.ufpa.br*]
Walter dos Santos Oliveira Júnior [Inteceleri Technology for Education | *walter@inteceleri.com.br*]
Diego Lisboa Cardoso [Federal University of Pará | *diego@ufpa.br*]
Marcos César da Rocha Seruffo [Federal University of Pará | *seruffo@ufpa.br*]

Institute of Technology, Federal University of Pará, St. Augusto Corrêa, 01, Guamá, Belém, PA, 66075-110, Brazil.

Abstract.
The use of Virtual Reality (VR) headsets has rapidly expanded into various areas, going beyond entertainment and electronic games. These devices provide immersive experiences that simulate three-dimensional environments, allowing for greater user interaction and engagement. Given the growth of mobile VR, this study presents MiritiBoard VR, a low-cost headset made from miriti, a plant native to the Amazon, focusing on sustainability, promotion of the local bioeconomy, and geometry education for basic education students in Brazil. The device was used in the educational application GeoMeta, enabling the visualization of 360-degree content, Augmented Reality, and gamification for geometry teaching. In order to improve the user experience of the MiritiBoard VR, two prototypes with controllers were developed to offer more features and comfort to the glasses, as it has limitations in mobility and interactivity. One prototype has a control integrated into the viewer and the other uses an external GamePad, both connected via Bluetooth, which is housed inside the headset. The evaluation, conducted using the System Usability Scale (SUS), showed that although the conventional model achieved the highest overall score, the MiritiBoard with integrated control was the users' preferred choice. The results indicate that MiritiBoard VR offers an immersive experience comparable to more expensive devices, with potential for expansion through new sensors. In addition to contributing significantly to mathematics education, the project reinforces responsible consumption practices and supports the local Amazonian economy.

Keywords: Joystick, Headset VR, Customization, Usability

Edited by: Ticianne Darin | **Received:** 06 April 2025 • **Accepted:** 07 January 2026 • **Published:** 23 January 2026

1 Introduction

In the contemporary technological landscape, Virtual Reality (VR) and Augmented Reality (AR) technologies are experiencing accelerated expansion across various sectors such as medicine, engineering, business, and education [Zhao *et al.*, 2023]. The immersion and interactivity provided by these tools offer disruptive potential for the teaching-learning process, enabling the creation of more engaging, personalized, and effective experiences [Ardiny and Khanmirza, 2018]. In education, VR headsets are used to facilitate the learning of complex content, such as science and mathematics, by offering 3D visualizations and interactive environments [Bogusevschi *et al.*, 2020]. Coupled with the expanded access to smartphones, a global phenomenon that has profoundly transformed how people communicate, access information, and seek entertainment, mobile VR applications have become increasingly popular with the advancement of mobile technologies and the greater availability of VR-compatible mobile devices [Smith *et al.*, 2011].

Mobile VR headsets function by connecting a smartphone to the headset, utilizing the device's screens and sensors to create immersive 3D experiences, where the user can interact with virtual environments at a low cost [Cochrane, 2016]. The popularity of mobile VR headsets has increased due to their accessibility, low cost, and ease of use, compared to more advanced VR systems with dedicated devices, making their use considerably more convenient and widespread [Papachristos *et al.*, 2017]. However, challenges such as acquisition costs, equipment maintenance, and the demand for specialized content development for mobile devices still represent barriers to the democratization of this technology, particularly in countries with limited resources [Yeung *et al.*, 2021], which is the context of the Brazilian Amazon.

In this context, the educational technology company Inteceleri[1] has developed the MiritiBoard VR headset[2], a low-cost, eco-friendly VR headset that stands out as an innovation in the educational field. It is an Head-Mounted Display (HMD) for mobile applications, constructed of miriti, a fiber extracted from the buriti palm, a tree endemic to the Amazon region. The device is part of the EduTech Amazon project[3] and is

[1] `https://inteceleri.com.br`. Accessed: 8 January 2026.
[2] `https://inteceleri.com.br/miritiboard-vr`. Accessed: 8 January 2026.
[3] `https://sites.google.com/gedu.demo.inteceleri.com.br/projetoedutechamazon/o-projeto`. Accessed: 8 January 2026.

utilized in the educational application *GeoMeta: Learn Geometry in the Metaverse*, which incorporates VR technology for teaching plane and spatial geometry in a gamified manner. The application is available for free download on the Play Store[4].

However, this HMD currently presents certain limitations in terms of mobility and interactivity, which represent challenges to be overcome and opportunities for further research and applications. Since the smartphone is housed inside the MiritiBoard VR, its touchscreen becomes inaccessible for manipulation, rendering the use of a virtual joystick impossible. The headset lacks any kind of buttons or controllers, limiting its application to games and software that utilize the smartphone's gyroscope and accelerometer, where navigation within the application is achieved through the player's body movements. The absence of dedicated controls considerably restricts the user's interaction with the virtual environment, limiting the variety of possible actions. This restriction directly impacts the gaming experience, making it less dynamic and immersive, while also reducing the potential to explore functionalities that require greater precision and rapid response.

In this context, the prototype named MiritiBoard VR with Integrated Controllers (MBIC) was developed. This iteration incorporates two tactile buttons and an analog joystick mounted on the sides of the headset. The developed hardware was programmed using the ESP32 microcontroller board, chosen for its integrated Bluetooth and Wi-Fi sensors, high processing power, and low energy consumption. The design required the addition of head-mounting straps to the HMD to secure it to the user's head, thereby freeing their hands to operate the controls, and a soft-edged padding was added to the areas contacting the player's face for comfort. Acknowledging that many commercial VR headsets utilize controllers — both integrated and external — a usability comparison was conducted with a version employing an external gamepad. This model, named MiritiBoard with External Controller (MBEC), utilized the 8BitDo Ultimate 2.4g Wireless GamePad. Both enhanced versions communicate to the smartphone via a Bluetooth connection. Since the use of controllers is not feasible within the educational application GeoMeta, it was necessary to test the controllers in other mobile applications. For this purpose, a specific virtual environment was developed to conduct the quantitative usability tests.

To validate the developed adaptations, the impact of controllers on the MiritiBoard VR compared to its conventional version must be measured on the gaming experience using User Experience (UX) techniques with a sample audience. The tool employed in this work was the System Usability Scale (SUS) method, a 10 item questionnaire. It was particularly suitable for this application because it is simple and quick to administer, preventing respondent fatigue. It possesses high scalability, is used for a wide range of interactive system evaluations, and is reliable, efficient, and widely accepted by both academic and professional communities [Ng *et al.*, 2011]. The SUS score ranges from 0 to 100, facilitating the comparison of different systems and product versions, in addition to allowing for an objective analysis of overall usability. Furthermore, it enables heuristic evaluations, as its questions allow for the correlation and inference of usability heuristics, thereby enriching data analysis [Wahyuningrum *et al.*, 2020]. It should be noted that the questionnaire used in data collection was a version translated into Portuguese and adapted to the scenario in which it was applied, generating biases and limitations in the results obtained, and not validated according to the original scale.

This article is an extended version of the paper in Portuguese entitled *Integração de Periféricos no MiritiBoard VR: Análise de Usabilidade e Preferências* — Free translation to english: Integration of Peripherals in MiritiBoard VR: Usability and Preference Analysis — published in the proceedings of the III Workshop on Interaction and Player Research in Game Development (WIPlay 2024) [Oliveira Júnior *et al.*, 2024]. The prior study describes a data collection conducted at a public event, where visitors were invited to try the three versions of the MiritiBoard set up on a table and to respond to an online form. This form contained information about the research, three preliminary questions, and the SUS questionnaire. The results showed that the MBIC version (with integrated controllers) had the best reception among respondents, with a 50% preference rate compared to the other models. However, the SUS score indicated the Conventional MiritiBoard VR (MBC) as the highest-rated, achieving a score of 86.50, though with a small margin over the other models, all of which were also very highly rated.

This present work provides a more comprehensive account of the theoretical underpinnings, motivation and justification for the adaptations, a detailed description of the prototyping process, a more in-depth discussion of the obtained results, and new metrics were calculated based on the collected data, a statistical treatment for the data, limitations of the results obtained and future works. The primary contribution of this article is the calculation of Nielsen's heuristics, which were inferred from the study, namely: Efficiency, Learnability, Memorability, Error Prevention, and Satisfaction. These provide additional, crucial usability information that significantly contributes to hypothesis testing.

This work is structured into seven distinct sections: Section 2 presents the background and theoretical foundation for a better understanding of the remainder of the article. Section 3 discusses works related to the article's proposal, examining applications of GamePads in mobile games and usability evaluation using the SUS method. Section 4 outlines the methodological path of the developed work, including the tools used and data collection procedures. Section 5 addresses the ethical considerations regarding data collection involving human subjects. Section 6 discusses the results following data analysis. Finally, Section 7 presents the article's final considerations, including the conclusion, limitations and future perspectives.

2 Theoretical Background

2.1 Low-Cost Metaverse Applications

The Metaverse refers to a shared virtual space, created through the confluence of VR and AR technologies, enabling users to interact with each other in a more efficient and engaging

[4]`https://play.google.com/store/apps/details?id=com.Inteceleri.Geometa&pcampaignid=web_share`. Accessed: 8 January 2026.

manner [Lemes *et al.*, 2024]. This type of interaction has the potential to radically transform project management and decision-making processes, allowing for the integration of this space into a wide range of contexts—from educational settings to Industry 4.0 applications—by merging virtual and physical environments to enhance efficiency and collaboration among users [de Souza *et al.*, 2025]. Furthermore, it has been applied in professional training, flight simulators, healthcare fields such as virtual therapies and surgeries, and even in virtual tourism [Moline, 1997].

In the educational context, the Metaverse can currently be employed in various ways, possessing the potential to transform the notion of learning by making it more interactive, efficient, and engaging for the user [Brito and Medeiros, 2025]. This mode of utilizing such a space enables its users to develop digital skills, as the interaction among multiple users to solve more complex tasks fosters improved communication, collaboration, and autonomy. The tool requires a certain level of independence from the user to learn and explore the provided environments, further promoting self-directed engagement [Guimarães *et al.*, 2022].

However, despite its diverse scopes and application possibilities, the employment of the Metaverse in these contexts still faces a series of challenges, both in its effective implementation and development. Among these difficulties, notable issues include unequal access to digital technologies [Vianna *et al.*, 2024], difficulties in the reproduction of human gestures and expressions by avatars, which limits the immersion experience; the scalability of the virtual world, restricting the number of users in the space without compromising connection to the Metaverse [Silva, 2023]; and finally, the high cost of producing equipment necessary for immersion [da Silva *et al.*, 2023].

Overcoming these obstacles is crucial for AR and VR technologies to reach their full transformative potential across various sectors of society. In the Brazilian Amazon, riverside communities face serious economic and social challenges that prevent the population from enjoying basic rights such as healthcare, education, and electricity, which directly impact their educational deficit [Ferreira and Silva, 2021]. Inadequate infrastructure is one of the main barriers, with numerous districts in these regions suffering from a lack of basic resources such as internet access, technological equipment, and essential educational materials, further contributing to their isolation from the rest of the country [Batista *et al.*, 2021].

The pursuit of equity and inclusion in access to these tools drives the development of more accessible devices [Persson *et al.*, 2015]. The need to address the demands of students with disabilities, learning disorders, or those in socioeconomically vulnerable situations justifies the creation of tools that allow for the adaptation of content and pedagogical activities to the individual needs of each student [Creed *et al.*, 2024]. The use of technologies such as VR and AR, combined with the principles of universal design developed by Ronald Mace [Mace, 1998], can enable the creation of devices that offer multiple means of representation, engagement, and expression, promoting the inclusion and active participation of all students in the learning process [Al-Ansi *et al.*, 2023].

2.2 Application of Miriti

The palm tree *Mauritia flexuosa*, commonly known as "*buritizeiro*" or "*miritizeiro*," is a palm species typical of tropical regions in South America, primarily found in the Amazon and Cerrado biomes [Vieira, 2017]. The buriti palm is highly adapted to wetland areas and is essential for local fauna and riverine communities, which utilize its fruit (buriti), leaves, and stem for nourishment and handicrafts [Amarante Jr *et al.*, 2015]. Its fiber, known as miriti, possesses specific physical characteristics that allow for diverse applications. The plant material's low density, approximately $6 \times 10^{-2} g/cm^3$, is a direct result of the structural arrangement of oriented and aligned cellulose fibers, earning it the nickname "the Styrofoam of the Amazon" [Barbosa and Porfírio, 2021].

Today, miriti toys are recognized as an intangible cultural and historical heritage of Pará, as established by State Law No. 7,433, sanctioned on June 30, 2010 [Ferreira Júnior, 2015]. This cultural manifestation originated in Abaetetuba, a city located on the banks of the Tocantins River in Pará, and has gained international prominence through the *Círio de Nossa Senhora de Nazaré*, one of the largest religious celebrations in the world. During the festival, miriti toys are widely sold at fairs and stalls, solidifying their role as an essential part of local popular tradition [da Silva *et al.*, 2013].

After undergoing laboratory characterization, miriti has revealed unique properties and proven to be a natural material suitable for numerous structural and functional applications, with notable use in initiatives that promote both local economies and environmental conservation [Santos and Coelho-Ferreira, 2011]. In education, miriti holds significant applications. It is used as didactic material in science education, leveraging its physical properties, such as low density, porosity, and photosensitivity, for experiments like buoyancy studies in hydraulics and physical optics demonstrations [Torres, 2021]. It is also integrated into pedagogical projects aimed at teaching biodiversity, sustainability, and regional culture, raising awareness among children and youth about the importance of environmental preservation and the value of local cultural traditions [Agostinho and Reis, 2024].

2.3 MiritiBoard VR

Aiming for sustainability and low cost, the MiritiBoard VR, registered under the patent [Oliveira Júnior and Matos, 2019], was developed as a mobile VR headset made from plant-based material, promoting the bioeconomy and valorizing local culture. Developed in 2016 by Inteceleri, a startup specialized in educational technologies, it is used in the company's products, such as the educational application *GeoMeta*, integrated into the *EduTech Amazon* project. The VR device provides an immersive experience to the user through the simple use of a smartphone, which is attached to the viewer and functions as the display for the VR experience. Its use also extends to other VR applications, such as French language learning[5], as well as simulators, fairs, and exhibitions in public events. Its application is not limited to the developer's own products, broadening its potential use across diverse educational, cultural, and interactive contexts.

When played with the aid of the MiritiBoard VR headset,

[5] `https://bit.ly/3NsAeWI`. Accessed: 8 January 2026.

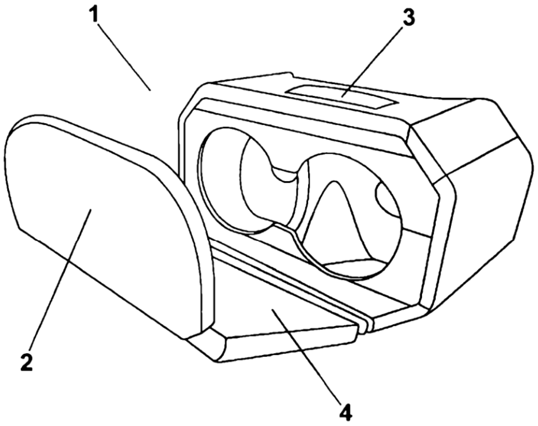


Figure 1. Front view of the schematic representation of the MiritiBoard VR.

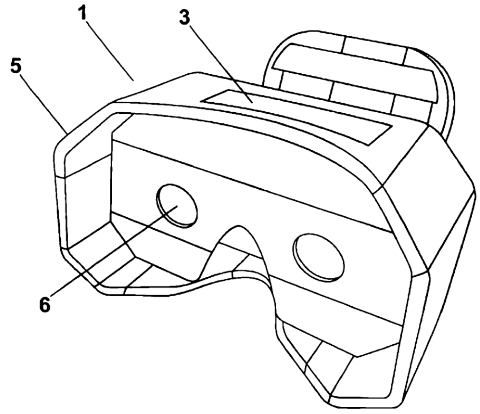


Figure 2. Rear view of the schematic representation of the MiritiBoard VR

the GeoMeta application offers an immersive and interactive experience within a 3D environment that applies geometric shapes in various locations around the globe, utilizing pattern recognition. The tool has been validated through its application in several elementary schools, involving a sample group of 343 students from eight public and private institutions in Belém, Pará state [Estevam *et al.*, 2024]. During these sessions, a comparative evaluation was conducted between the students' prior knowledge and the knowledge acquired after using the application. The results indicated a significant improvement in the understanding of geometric concepts across all participating schools, with an increase of up to 81.82% in scores between the initial and final assessments [Oliveira Júnior *et al.*, 2023]. In total, the EduTech Amazon project has already impacted over 700,000 students across the Brazilian Amazon, extending beyond the state of Pará [dos Santos *et al.*, 2023].

It's feature replicability inspired by Google Cardboard, a cardboard VR headset launched by Google in June 2014 [Fabola *et al.*, 2015]. The MiritiBoard VR follows an open-project approach, allowing anyone to download the component templates, available in the footnote[6], and build their own device. To use it, only a smartphone equipped with a gyroscope and accelerometer — essential sensors for the immersive experience — is required. The phone is housed within the headset, as demonstrated in the product presentation video provided in the footnote[7]. It offers students and teachers immersion in various virtual environments, making learning more dynamic, interactive, and engaging.

The material used for producing the headset originates from Marajó Island, and its manufacturing is carried out in the municipality of Abaetetuba, both in Pará. Its design is inspired by rustic toys and consists of thirteen flat pieces of miriti that are cut, sanded, and glued together using hot glue. These pieces connect to form a device that, when combined with a smartphone and a VR application, enables the VR experience. The manual construction of the MiritiBoard VR stimulates users' creativity and autonomy. In addition to sustainability and accessibility, the MiritiBoard VR offers other advantages such as water resistance — it can be wetted without damage -customization, allowing users to paint and decorate it with materials of their choice, and easy maintenance, as any damage can be repaired in a practical, safe, and economical manner. It aims to innovate the classroom by using raw materials that are closely tied to the daily lives of people in the Amazon region.

The aforementioned eco-friendly headset, depicted from the front in Figure 1, consists of a front lid (2) equipped with a Velcro strap (3) to fasten it to the upper part of the headset (1). This front lid (2) features a compartment (4) for housing the smartphone. The rear section, shown in Figure 2, includes a contoured edge (5) designed for ergonomic contact with the face and two biconvex lenses (6) with a diameter of 25 mm. With dimensions of 15 cm × 9 cm × 9 cm and a lightweight structure, the MiritiBoard VR is compatible with most iOS and Android smartphones ranging from 4.7 to 5.2 inches. Beyond its applications in entertainment and events, the MiritiBoard VR aims to transform the teaching of mathematics and geometry, innovating the classroom through the use of raw materials native to the Amazon.

2.4 Challenges

In the context of mobile games, avatar control and in-game navigation have traditionally been managed through virtual controls—an interface that simulates the functions of a physical controller on a touch-sensitive screen [dos Santos, 2022]. However, this system is unfeasible for VR games where the device is attached to a headset, as is the case with the MiritiBoard VR, where the smartphone is housed in the front lid, illustrated in Figure 1. This configuration is because the player cannot access the phone's screen to manipulate the virtual joystick. Consequently, this VR headset is designed for applications that utilize the smartphone's gyroscope and accelerometer, where navigation is achieved through a reticle at the center of the screen. The player selects objects by focusing on them through movement of the torso or neck.

With the advancement of mobile devices, dedicated controllers and other peripherals for smartphones have emerged, enriching the gaming experience. An inspiring example is the Samsung Gear VR model[8], a mid-cost VR headset developed by Samsung in partnership with Oculus, launched in 2015.

[6] `https://bit.ly/4sOGZCn`. Accessed: 8 January 2026.

[7] `https://youtube.com/watch?v=EiHYu7XVGcE`. Accessed: 8 January 2026.

[8] `https://www.samsung.com/br/support/model/SM-R323NBKAZTO/`. Accessed: 8 January 2026.

Similar to the low-cost models previously discussed, it used a Samsung smartphone housed within it as both display and processor, offering an accessible VR experience for users of the brand's phones. It featured multiple strap adjustments for secure fitting and an integrated touchpad on the right side of the headset itself, allowing users to navigate menus, along with "back" and volume control buttons. These were connected to the phone via a physical micro-USB or USB-C cable, depending on the phone model. Several updates were released for the Gear VR to improve comfort, most notably the integration of an external Bluetooth controller in 2017 to enhance gameplay [Tranton, 2016].

The integration of controllers into the MiritiBoard VR faces several inherent limitations of the viewer, which are also shared with its inspirational model, the Google Cardboard. These include comfort-related issues associated with the use of the headset: the device, with the smartphone housed inside, has considerable weight, and the user must support the entire assembly with both hands. This can lead to arm fatigue and exhaustion during extended sessions, as the device lacks any form of head strap or secure fixation. Additionally, discomfort arises from the splinter-prone nature of the miriti fiber, which contacts the user's face and may cause irritation or minor injuries due to its rough texture, further hindering prolonged usage. These limitations impair navigation in complex virtual environments and the execution of tasks requiring greater physical interaction, resulting in reduced user engagement. Players may choose to engage only for shorter periods, ultimately compromising the effectiveness of the application across educational, commercial, and entertainment contexts.

Consequently, there is a clear need to adapt controllers to the HMD to enhance gameplay and immersion in the VR experience, while also addressing inconveniences such as the lack of secure fastening and facial discomfort. For the successful integration of controllers, it becomes imperative to improve the comfort and stability of the headset during use, ensuring a more convenient and extended gameplay experience, thereby increasing user retention. Given the two primary options for controllers — integrated in the HMD or external — a usability study is essential to determine which alternative is more convenient and better accepted by players within a specific sample. User Experience (UX) techniques will be applied to quantitatively measure and compare both options.

2.5 Usability Evaluation

The method employed to measure which of the three models is most accepted by users was the System Usability Scale (SUS) algorithm. The SUS score is a widely used metric to evaluate the usability of a system, interface, or digital product [Grier *et al.*, 2013]. Developed by John Brooke [Brooke, 1996], the scale consists of 10 multiple-choice questions where users indicate their level of agreement using a Likert scale ranging from 1 to 5, with the lowest extreme meaning "strongly disagree" and the highest extreme meaning "strongly agree."

Indeed, it is a widely used usability evaluation tool designed to measure the ease of use of products, systems, and interfaces. It is regarded as a rapid, effective, and economical method for obtaining feedback on usability and is extensively applied across various fields, including software development, product design, and human-computer interaction research [Boucinha and Tarouco, 2013].

The odd-numbered questions present positive statements about the system's usability, while even-numbered questions present negative statements. This alternation between positive and negative assertions helps mitigate response bias by ensuring participants thoughtfully evaluate each item rather than providing automatic or patterned answers. The ten statements are as follows:

1. I think I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I found the system easy to use.
4. I think I would need the help of a person with technical knowledge to be able to use the system.
5. I thought that the various functions of the system were well integrated.
6. I thought there was a lot of inconsistency in the system.
7. I imagine that most people would learn to use this system quickly.
8. I found the system very complicated to use.
9. I felt very confident using the system.
10. I had to learn a lot of new things before I could use the system.

For the odd-numbered questions (1, 3, 5, 7, 9), subtract 1 from the score given by the user. For the even-numbered questions (2, 4, 6, 8, 10), subtract the user's score from 5. Then, sum all the adjusted values and multiply the total by 2.5, resulting in a final score ranging from 0 to 100. This score does not represent a percentage but rather a usability index, where values above 80.3 indicate excellent usability, scores between 68 and 80.3 suggest good usability, and scores below 68 point to potential usability issues. The final score for the prototype is calculated using Equation 1, where X_i and X_j represent the Likert scale scores for the odd and even numbered questions, respectively.

$$SUS = \left(\sum_{i=odd} (X_i - 1) + \sum_{j=even} (5 - X_j) \right) \cdot 2.5 \quad (1)$$

The indexes i and j are given by

$$i = \{1, 3, 5, 7, 9\}, \qquad j = \{2, 4, 6, 8, 10\}.$$

And the variables X_i and X_j vary as follows

$$1 \leq X_i, X_j \leq 5, \qquad X_i, X_j \in \mathbb{N}.$$

However, the SUS questionnaire used for data collection in this study is not the original list described by Brooke, which was created in British English. Instead, it is an ad-hoc translation into Brazilian Portuguese with adaptations tailored to the specific context of this research, as will be detailed further in subsection 4.6. Language changes and cross-cultural adaptations can introduce biases and affect the SUS score, as explored in the work of [Lourenço *et al.*, 2022], where a version of the SUS was translated into Brazilian Portuguese following a cross-cultural translation methodology and validated by experts.

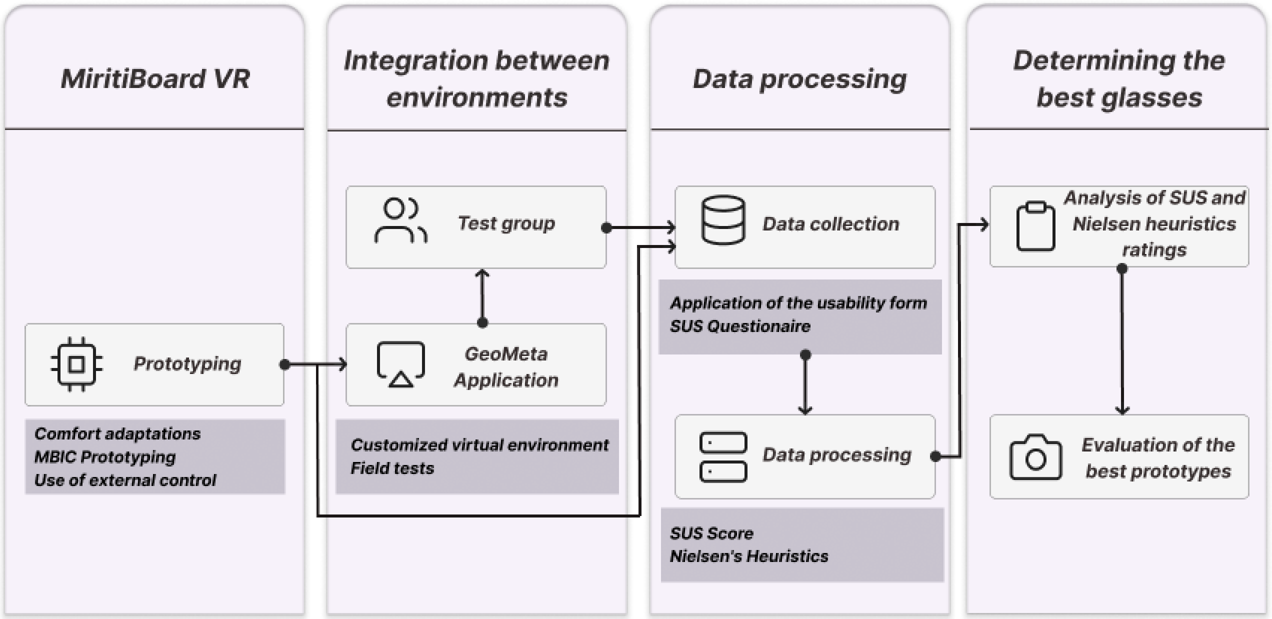


Figure 3. Flowchart of the methodology.

Based on the SUS questionnaire, it is possible to correlate and infer usability heuristics. The Nielsen's Heuristics are a set of principles developed by Jakob Nielsen in 1990 [Nielsen and Molich, 1990], which introduced five usability goals and eight heuristics. These were later expanded to ten heuristics in subsequent work [Nielsen, 1994]. The goals represent abstract objectives, while the heuristics serve as concrete tools for achieving these goals, guiding the evaluation of interface usability. These tools assist designers and developers in identifying and addressing UX issues through metrics and principles. The heuristics are not rigid rules but rather guidelines that facilitate the development of intuitive and efficient interfaces. Each question in the SUS can be associated with one or more heuristics, helping to pinpoint which aspects of the interface require improvement. The usability goals are listed below.

1. Efficiency
2. Learnability
3. Memorability
4. Error Prevention
5. Satisfaction

These 5 metrics will be quantified based on the answers to the SUS questionnaire and the correlations shown in Table 1, which will be normalized to a score from 0 to 100 according to the equations below:

$$\text{Learnability} = \frac{Q_3 + Q_4 + Q_7 + Q_{10}}{16} \times 100$$

$$\text{Efficiency} = \frac{Q_5 + Q_6 + Q_8}{12} \times 100$$

$$\text{Memorability} = Q_2 \times 25$$

$$\text{Error Prevention} = Q_6 \times 25$$

$$\text{Satisfaction} = \frac{Q_1 + Q_4 + Q_9}{12} \times 100$$

Given that the SUS score and questionnaire are powerful tools for obtaining information about usability, with the inference of heuristics, we will use them as an evaluation method for the developed prototypes.

Table 1. Correlation between Nielsen's Usability Objectives and SUS Questions.

Usability Objective	Correlated SUS Questions
Learnability	Question 3, Question 4, Question 7, Question 10
Efficiency	Question 5, Question 6, Question 8
Memorability	Question 2
Error Prevention	Question 6
Satisfaction	Question 1, Question 4, Question 9

3 Related Work

The present section introduces related work concerning the use of the SUS for usability analysis of VR applications artifacts and their peripherals. These studies yield insightful results regarding the use of low-cost AR and VR devices for the digital inclusion of diverse users.

In this context, research on low-cost headsets and open-source/3D-print projects has been seeking to make VR more accessible, while also evaluating ergonomics and usability. In this regard, an important milestone was the release of the Google Cardboard specifications, which standardized optical parameters and integrated buttons into the headset itself, enabling interaction without external controllers while also guiding compatible projects through a viewer profile [Perla and Hebbalaguppe, 2017].

Regarding design and low-cost smartphone-based HMDs, there are proposals that explore the architecture and performance/ergonomics trade-offs, such as the smartphone HMD prototype by Lee *et al*. [2020], as well as a low-cost HMD design that uses the phone as a display module in Olson *et al*. [2011]. Beyond the CardBoard ecosystem, modular and 3D-printable HMDs have emerged, such as VEGO, which adopts modularity, adjustable IPD, and reproducible parts, aiming at cost reduction Hazarika and Rahmati [2023].

Regarding usability/ergonomics evaluation, works such as Papachristos *et al*. [2017], which through comparative studies between premium headsets and low-cost mobile solutions, such as Oculus Rift vs. mobile headsets, indicated that in certain educational scenarios there were small differences in satisfaction and learning, suggesting that low-cost platforms are viable when the content and tasks are appropriate.

Similarly, in Mehrfard *et al*. [2019], reviews and comparative analyses of HMDs highlight metrics such as comfort, neck fatigue, heating, and readability, which are useful for guiding hardware evaluations. In mobile VR environments, studies using SUS demonstrated acceptable usability for tours and educational experiences, reinforcing that the physical design of the headset and ease of use directly influence the experience Othman *et al*. [2022].

In agreement with these works, MiritiBoard VR customizations stands out by integrating tactile buttons and a joystick directly into the headset, eliminating the need for external controllers and offering improved ergonomics with simple adjustments and comfortable materials. Unlike Cardboard, which is limited to a single button, MiritiBoard prototypes here presented expands interaction possibilities while maintaining low cost and ease of assembly, addressing the usability and comfort gaps highlighted in the literature.

4 Methodology

The study's methodology involved the development of a customized prototype of the MiritiBoard VR to integrate controllers directly in the headset and enable customization with peripherals. To validate the developed prototype, a usability comparison was conducted between the unmodified conventional MiritiBoard VR (MBC), the version with integrated controllers (MBIC), and the version with an external gamepad (MBEC), with each prototype offering a distinct approach to navigation and interaction within the virtual environment. For this usability study, it was necessary to create an open-world game to ensure adequate immersion in the virtual environment when using controllers, as well as to adapt mounting solutions for improved comfort. The flowchart summarizing the adaptations addressed in this section is presented in Figure 3.

4.1 Comfort Adaptations

To increase comfort, an EVA (Ethylene Vinyl Acetate) rubber edge, a soft polymeric material, was added around the areas in contact with the face, as illustrated in Figure 4. Two alternative fastening solutions were then proposed: the first consists of an adjustable strap that wraps around one hand, securely fixing the headset and allowing the player to move with greater stability, as shown in Figure 5. The second solution involves a strap that encircles the player's head, as illustrated in Figure 6, eliminating the need to hold the headset and smartphone, enabling longer gaming sessions without causing fatigue and freeing the hands for the use of a GamePad or other devices for interaction within the virtual environment. The development of such control devices will be detailed in the following subsections.

Figure 4. EVA edge in the area of contact with the face.

Figure 5. Side hand strap.

Figure 6. Fastening straps around the head.

4.2 MBIC prototyping

To ensure smooth interaction in the virtual environment, two tactile buttons were installed, functioning as selection and menu return commands, along with an integrated analog joystick module that allows the user to move within the virtual space, mounted on opposite sides of the headset. The prototyping of these components integrated into the HMD was carried out with the ESP32 WROOM-32 microcontroller board, responsible for processing user inputs and handling Bluetooth communication with the smartphone. This board was chosen for its low cost, low power consumption, versatility, and high processing power, featuring a 32-bit Xtensa LX6 CPU, superior to the 16-bit Arduino, and designed for IoT (Internet of Things) applications with native Wi-Fi and Bluetooth support. Communication between the ESP32 and the peripherals occurs through jumper cables, connecting the essential components required for the operation of the integrated controller.

The Figure 9 illustrates the circuit of the MiritiBoard with Integrated Control (MBIC), assembled in the Wokwi software. This is an online platform for simulating and programming digital projects, allowing the creation and simulation of electronic circuits, as well as the programming of microcontrollers such as Arduino, ESP32, ESP8266, among others. The circuit was powered by two 3.7 V lithium batteries with a capacity of 1200 mAh, providing sufficient autonomy for extended sessions without interruptions. The programming of the microcontroller board was carried out in the Arduino

IDE software using C++, available at the bottom of this page [9], with this code controlling the previously defined peripheral functions, and its logic being represented by the pseudocode in 1.

It is also worth highlighting the use of the BleGamePad library [10], which is essential for the operation of the MBIC. This library acts as an intermediary between the buttons and the analog joystick connected to the device, translating their inputs into encoded commands and sending them via Bluetooth. In this way, it enables an efficient interface between the user and the computer, ensuring a smooth and intuitive experience. Furthermore, thanks to its implementation, the MiritiBoard becomes a plug-and-play device, meaning it can be used immediately on any Bluetooth-enabled smartphone without the need for additional configuration.

Algorithm 1 Pseudocode for MBIC control

```
Start serial communication
Set CPU frequency to 8 MHz
Disable Wi-Fi
Configure button and hat pins as inputs with pull-up
Start gamepad
Disable automatic reporting on the gamepad
while gamepad connected do
    Read analog values of X and Y
    Map values to the range of 0 to 32737
    Update gamepad "thumb" movement
    for each hat button do
        if hat button pressed then
            Update direction on gamepad
        else
            Reset hat to center position
        end if
    end for
    for each physical button do
        if button pressed then
            Press button on gamepad
        else
            Release button on gamepad
        end if
    end for
end while
```

With the circuit assembled and tested, the physical structure of the MBIC was designed to ensure comfort and stability during use. The circuit and peripherals were mounted on the MiritiBoard with an EVA rubber edge and head-encompassing fastening straps. The selection buttons were positioned on the right side of the display, the analog joystick on the right side, the ESP32 board was fixed between the Velcro and the joystick, and the battery was attached to the front cover, as shown in Figures 7 and 8. All these components were secured using hot glue, with the jumper wires routed through drilled holes.

The arrangement of the side controllers and the use of head-encompassing fastening, due to the additional weight of the modifications, make it more convenient to ensure stability and comfort. In this way, the MBIC seeks to provide enhanced navigation and intuitive interaction, combining electronic prototyping with an ergonomic design adapted to the user's needs.

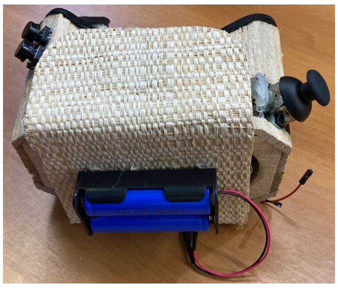


Figure 7. Front view of the MBIC.

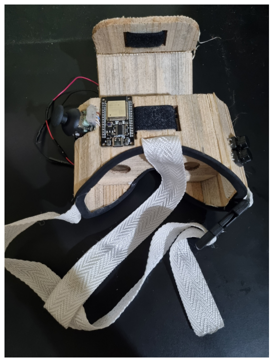


Figure 8. Rear view of the MBIC.

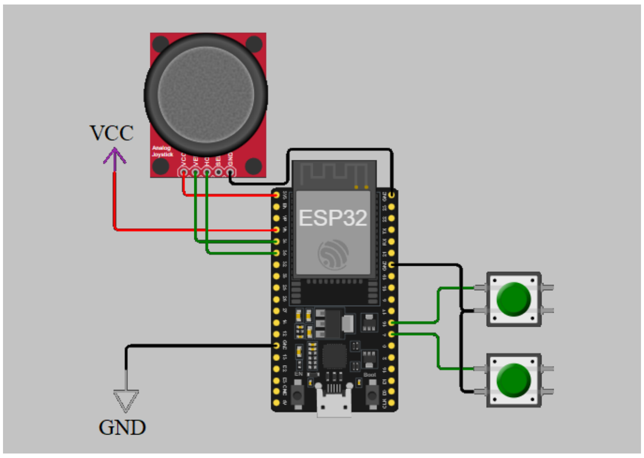


Figure 9. MBIC Circuit

4.3 External control used

For the usability study, it was considered appropriate to compare the developed model with one using an external controller, since other VR headset products have implemented both possibilities. The MiritiBoard with External Control (MBEC) makes use of the 8BitDo Ultimate 2.4 GHz GamePad Joystick in black color, connected via Bluetooth to the smartphone, which is attached to the headset during gameplay, as shown in Figure 10.

This controller was selected due to its extensive battery autonomy of up to 15 hours, enabling long, uninterrupted usage sessions; its Bluetooth connectivity capability with smartphones; and its intermediate cost coupled with satisfactory quality [Maggiorini *et al.*, 2019]. These characteristics make it an excellent choice for prolonged immersion in virtual environments, offering both practicality and high-performance functionality.

Furthermore, users may employ other types of Bluetooth controllers can be used according to the user's preference or availability in terms of reproducibility of the work, such as console joysticks the player may already have at home,

[9]`https://github.com/joaofmcarvalho/C-digo-Placa-ESP32/blob/main/esp32.cpp`. Accessed: 8 January 2026.

[10]`https://github.com/lemmingDev/ESP32-BLE-Gamepad`. Accessed: 8 January 2026.

like PlayStation and Xbox controllers, which were also tested during the development of the compatibility tests. In this configuration, the user employs both hands, making proper fastening of the VR headset essential, using the MiritiBoard VR with head-encompassing straps (Figure 6), to ensure efficient manipulation of the controller.

Figure 10. External control used in MiritiBoard VR.

4.4 Customized virtual environment for testing

To conduct the field test with users of the developed prototypes and their quantitative usability evaluation, it was necessary to develop an immersive virtual environment suitable for the experiment. The GeoMeta application, adapted for use with the MiritiBoard VR, restricts interaction to a single avatar with movements controlled by the smartphone's gyroscope, which detects the player's torso or neck movement, moving the camera within the 3D environment. Object selection and navigation are performed through a crosshair at the center of the screen, which the player focuses on the object of interest; a circular 2-second visual timer then triggers the selection if the target remains in focus long enough.

However, with the need to expand gameplay and test the integration of controllers into the headset, this game becomes impractical, as it does not support external physical devices. Given this limitation, a virtual environment was developed that properly supports controller integration. This game was created in the Unity development environment, a widely used platform for building interactive 3D experiences, using ready-made assets available online that provide good compatibility with external controllers, such as GamePads, and customized to make the artistic elements resemble GeoMeta equipped with controllers. This version allows free movement, where the player can freely explore a virtual open-world city (Figure 11) with GeoMeta elements (Figure 12), including vehicle traffic, squares, buildings, and other landscape features that enrich the immersive experience. This game can be downloaded from the footnote [11]. Other free open-world games that responded to the developed controllers were also tested during the public demonstration, but these were not used in the quantitative usability tests.

[11] https://drive.google.com/drive/folders/1olBrA9tAKVJhQHTM9B2vh2jy3V6ZVRAl?usp=drive_link. Accessed: 8 January 2026.

Figure 11. Map overview in perspective.

Figure 12. Matheus character at the gameplay start location.

4.5 Test Group

The test group was composed of visitors to the booth of Inteceleri at the *76ª reunião anual da Sociedade Brasileira para o Progresso da Ciência* (SBPC) [12], which took place on the campus of the *Universidade Federal do Pará* (UFPA; Federal University of Pará) from July 8 to 12, 2024 in the city of Belém. The visitors consisted of people of different ages, genders, and education levels. Many of the visitors were undergraduate students from UFPA, but there was also a large number of elementary school students from the municipal public education system who were on field trips.

No demographic data of the visiting public was collected, but it was observed that the group consisted of people with varying ages and educational backgrounds. A considerable portion were adults with little familiarity with technology, or minors for whom data collection was not feasible due to ethical reasons. There was an equivalent representation of male and female participants. Overall, the majority of respondents were undergraduate students from the institution where the data collection took place. This population largely consisted of young adults in their twenties, with extensive exposure to and familiarity with technology. Moreover, as higher education students, they had an advanced educational level compared to the general Brazilian population, considering that the enrollment rate of recent high school graduates in higher education in Brazil is 27%, according to INEP's 2023 Higher Education Census [Chiarini *et al.*, 2024].

The Inteceleri booth was located inside the Gamer Arena, where other game and simulator booths were arranged linearly, which visitors went through one by one, receiving a stamp in the guidebook they were given by the reception staff. Upon arriving at the testing booth, visitors encountered the three prototypes to be evaluated on a table and, with the assistance of the project's researchers, were able to freely try all three versions. The MBC was used with the original version of GeoMeta, while for the others, visitors were invited to play the open-world version using the prototypes with head straps and controllers, MBIC and MBEC.

[12] https://ra.sbpcnet.org.br/76RA/. Accessed: 8 January 2026.

The data on the use of the prototypes are presented in Section 6, where Figure 16 shows the intersection chart of the groups of prototype users, since visitors could test one, two, or all three prototypes in a randomized, non-uniform order. This order sampling factor may have introduced unquantified biases in the responses.

At the end of the exhibition, players over 18 years old, who demonstrated sufficient educational background and cognitive ability to interact with the prototypes, as well as familiarity with technology and smartphone use to access the form, were invited to complete an online questionnaire. This was facilitated by the researchers through a QR code printed on an A4 sheet placed on the table where the prototypes were displayed, which could be accessed using a mobile phone camera. Since only about one in every four visitors, on average, completed the questionnaire, it is estimated that more than 200 people visited the booth where the study was conducted. Many chose not to participate, particularly those with lower educational levels and limited familiarity with technology, who showed low adherence.

Figure 13. Visitor playing with MBEC.

4.6 Data collection

The data were collected through an online questionnaire in Brazilian Portuguese, created using the Google Forms platform [13], available in the footnote of this page, and composed of four sections.

The first page presents information about the purpose of the questionnaire, which is to collect data related to the use of the MiritiBoard VR prototypes, which are customized models designed for use with controllers. In the second section, participants were invited to either consent or decline to participate in the study after reading the *Termo de Consentimento Livre e Esclarecido* (TCLE; Informed Consent Form), which is detailed in Section 5, addressing the ethical considerations. It also provides information regarding the number of questions, the average time required to complete the form, and clarification that participation was voluntary and unpaid.

The third section of the questionnaire, titled "Information about your evaluation", contains three questions:

1. Which headset did you use?
2. Which headset will you evaluate?
3. If you used more than one headset, which one did you prefer to use?

[13]`https://forms.gle/ixM5bn7RQVjfuqhu5`. Accessed: 8 January 2026.

The available response options for these three questions were the three prototypes available for testing at the event: MiritiBoard GamePad (integrated controller), MiritiBoard VR with external controller, and MiritiBoard VR. Only the first question included an image of the three prototypes, as illustrated in Figures 14 and 15.

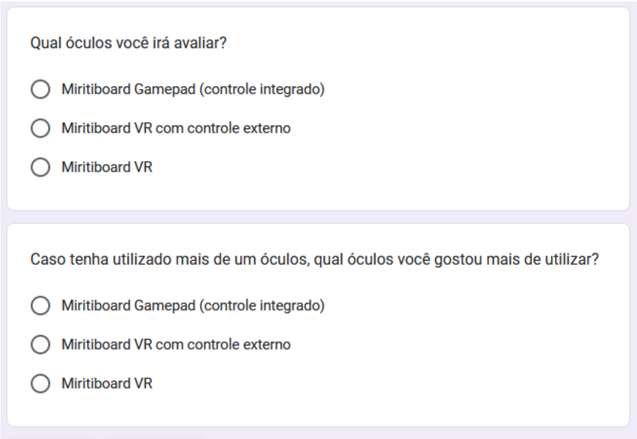
Figure 14. First question of section 3 in the form.

In the fourth section, participants answered the SUS usability questionnaire. This consisted of 10 statements adapted from those presented in Subsection 2.5, which are listed below:

1. I'd like to wear the glasses in my day-to-day life.
2. I found the glasses unnecessarily complex.
3. I found the glasses easy to use.
4. I think I would need technical support to use the glasses.
5. I found that the various functions of the glasses were well integrated.
6. I noticed a significant inconsistency in using the glasses and/or its controls.
7. I imagine most people would learn to use the glasses very quickly.
8. I found the glasses very complicated to use.
9. I felt very confident using the glasses.
10. I had to learn many things before I could start using the glasses.

Since the data collection was carried out with lusophone speakers, and was not directed at a system, but rather at a VR headset, which is a physical artifact, the authors deemed it necessary to make changes regarding Brooke's original questionnaire presented in Section 2.5. The version used in Portuguese and the validated consensual version translated into Brazilian Portuguese presented in [Lourenço *et al.*, 2022] can be accessed and compared in the footnote [14], where the word system is replaced by headset, and minor phrasing changes were made without altering the question's intention.

The process was carried out anonymously, without collecting any identifying information. The average time taken to fill in the form was estimated at five minutes. A total of 63 responses were obtained.


Qual óculos você irá avaliar?

- Miritiboard Gamepad (controle integrado)
- Miritiboard VR com controle externo
- Miritiboard VR

Caso tenha utilizado mais de um óculos, qual óculos você gostou mais de utilizar?

- Miritiboard Gamepad (controle integrado)
- Miritiboard VR com controle externo
- Miritiboard VR

Figure 15. Second and third questions of section 3 in the form.

4.7 Data Processing

The data from the Google Forms questionnaire were grouped and exported into a Google Sheets spreadsheet, saved as a Google Drive file. Using this file in .csv format as input, the SUS usability results were calculated in Google Colab, which can be accessed in the footnote [15], where a Python code was executed in an online compiler, generating the SUS score and Nielsen Heuristics as output. The SUS calculation code was original, based on the equations from [Brooke, 1996] and various manuals available online.

First, the initial Python code uses the pandas library to load and process a CSV file named "miritiboard-sus.csv", available in the footnote [16], which contains data collected through Google Forms and stored in Google Sheets. This file is then imported into Google Colab as input data for the equations described in subsection 2.5 related to usability, including the SUS score and the evaluation according to Nielsen's Heuristics.

A statistical analysis was also carried out to demonstrate the consistency of the collected data. It was developed in Python on Google Colab in a separate code, using the same .csv file as input. The calculated statistical parameters and their corresponding plots can be viewed at the Google Colab link available in the footnote [17], which will be further described in Section 6, dedicated to the discussion of the obtained results.

[14] `https://docs.google.com/spreadsheets/d/1xkFDxWvRnIsGGa3auKPRkMcGpNqHqunVOfL9UGENWw8/edit?usp=sharing`. Accessed: 8 January 2026.

[15] `https://colab.research.google.com/drive/1_zmlfazzWPWzVnfg-8kXsx9_3nbxpwda?usp=sharing`. Accessed: 8 January 2026.

[16] `https://docs.google.com/spreadsheets/d/1MOUGiscH9OlzkmaK8a6NQmqbbuXNW2V3wpDI5qXqR7O/edit?usp=sharing`. Accessed: 8 January 2026.

[17] `https://colab.research.google.com/drive/1gC8HzrjD9v-PI1h1PMJNVm1ZgyHRuznq?usp=sharing`. Accessed: 8 January 2026.

5 Research Ethics

The data collection was conducted through a form created on the Google Forms platform, where the first page contained the Free and Informed Consent Form (TCLE the acronym in portuguese). Information regarding the test group is described in subsection 4.5. Participants aged 18 and older were invited to read and either accept or decline the terms before proceeding to the usability questions in the form. In the TCLE, participants were fully informed that they were taking part in a research study. They received details about the study's objectives, potential risks and benefits, the project associated with the research, the identification and address of the researchers, contact phone number and email, assurance of transparency and respect for privacy, and confirmation that their responses would be handled in accordance with the Brazilian General Data Protection Law, the *Lei Geral de Proteção de Dados* (LGPD). The research project involving human subjects was submitted to and approved by the Research Ethics Committee, the *Comitê de Ética em Pesquisa* (CEP), possessing a Certificate of Ethical Appraisal Presentation, *Certificado de Apresentação de Apreciação Ética* (CAAE) under number: 85196124.7.0000.0018.

The responses to the form were collected anonymously and without identification. No personally identifiable or contact information, such as name, email, phone number, or sensitive personal details including age, address, national ID (RG the acronym in portuguese), or tax number (CPF the acronym in portuguese), was gathered. The study did not involve significant health risks to participants, such as electrical or mechanical hazards. However, during the VR gaming experience, certain potential risks could arise, such as cybersickness—a condition similar to motion sickness caused by prolonged exposure to digital environments, including computer screens, smartphones, virtual reality, or electronic games [Ramaseri Chandra *et al.*, 2022]. This condition may lead to disorientation, eye strain, and an increased risk of falls or accidents.

6 Results and Discussion

The highest-rated model in the SUS score was the conventional MiritiBoard VR, the MBC. It is worth noting that this version received a low number of responses, with only 10 (16.4%) opting to evaluate it, resulting in a sample size disproportionate to the other models. Among the customized prototypes, the best-rated was the MBIC, preferred by 50% of respondents. The results of the three questions in Section 3 of the form, which address the information preceding the SUS usability evaluation, are detailed below.

The first question in this section of the questionnaire was: "**Which headset(s) did you use?**". Which 35 (56.5%) used the MBC, 33 (53.2%) tested the MBIC (Figure 7), and 30 (48.4%) tried the MBEC (Figure 10), out of a total of 62 responses, where only one respondent to the SUS questionnaire of the 63 responses did not declare which glasses were used, and this response was discarded.

The Venn diagram available in Figure 16 illustrates the intersections among these three groups, indicating how many individuals used one, two, or all three prototypes. Specifically, 10 people tested both the MBIC and the MBC, 9 people used the MBEC and the MBC, 1 person tried the MBIC and the MBEC, and only 8 respondents experienced all three models. Of the total 62 respondents, 34 (54.8%) used only one of the three models, while 28 (45.2%) used two or three models.

The second question was answered by 61 respondents: "**Which headset will you evaluate?**" Accordingly, 28 (45.8%) evaluated the MBIC, indicating a majority preference for this model. In comparison, 23 (37.7%) evaluated the MBEC, showing that there was also significant interest in this model. On the other hand, only 10 (16.4%) evaluated the MBC, as illustrated in Figure 17. These data help to understand which models were more popular or preferred during the study and provide insights into participants' acceptance and interest regarding the different types of VR headset models.

Finally, 54 participants answered the third question: "**If you used more than one headset, which one did you like using the most?**" Among them, 27 (50%) preferred the MBIC, which likely stood out for offering a more direct and intuitive experience in the virtual environment. Meanwhile, 19 (35.2%) opted for the MBEC, highlighted for enabling more comfortable and freer navigation, although it did not reach the same preference level as the integrated control model. Eight participants (14.8%) showed a preference for the MBC. These values are illustrated in the chart in Figure 18. This latter model, being the simplest and with fewer features compared to the others, was less attractive to those who had the opportunity to try the more sophisticated prototypes.

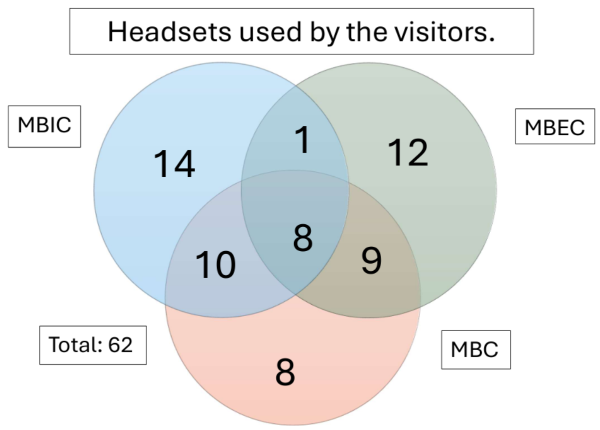


Figure 16. Venn diagram containing the answers to the first question, about which headsets were used.

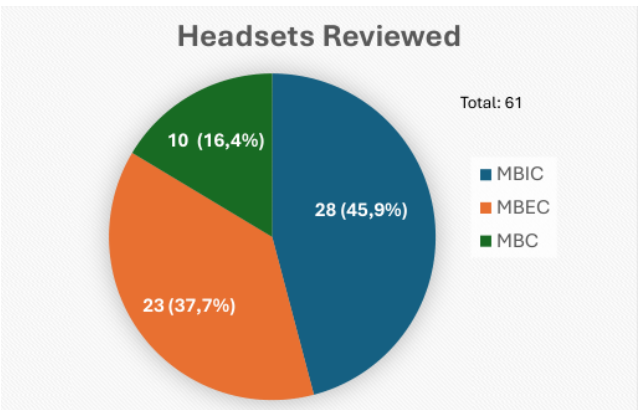


Figure 17. Values and percentages of the answers to the second question, about which headsets were evaluated.

The first inconsistency in the data was that this question was intended only for those who had used more than one model, whereas only 28 participants declared having tested two or three models, yet 54 people answered the question. Possibly, many expressed their preference without having used the other prototypes, making only a visual judgment from a distance by observing other players using them.

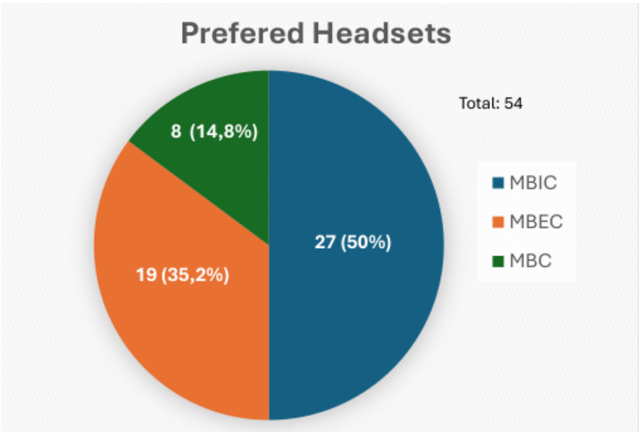


Figure 18. Values and percentages of the answers to the third question, on which headsets were preferred.

The Table 2 presents the SUS evaluation scores for the three prototypes, along with the arithmetic mean weighted by the sample size of each evaluated group, providing an overall score for all models, as well as the standard deviation of the scores relative to the mean. The MBC received the highest overall score of 86.5 out of 100, indicating that users considered it the most effective or comfortable in terms of usability, despite not being the most popular model. In second place, the MBIC obtained a score of 82.05. Although it was the most preferred prototype among users, with 50% preference, its lower SUS score compared to the conventional model suggests that, despite its popularity, its usability may have presented some shortcomings. Lastly, the MBEC received the lowest score, 79.24, which may reflect lower overall acceptance or some specific usability issues.

The overall average score of the evaluations was 81.9 out of 100, calculated using a weighted arithmetic mean that considered the number of evaluators for each model. The standard deviation of 3.07 shows that there was little variation in the scores among the prototypes, suggesting that all were well evaluated, with only subtle differences. The 7.26-point gap between the highest and lowest scores also reinforces that, although the scores varied, all prototypes received relatively high evaluations. The response frequency for each of the 10 questions in the 63 responses is shown in Figure 19, where a prevalence of responses at the extremes of the Likert scale (1 and 5) can be observed.

Based on the responses from the SUS questionnaire, five usability metrics were calculated, as described in subsection 2.5, and are presented in the chart in Table 1. A very low dispersion of results was observed, with a low standard deviation, indicating a highly concentrated distribution of scores. The MBC achieved the highest score across all five metrics used. The MBIC outperformed the MBEC in two metrics:

Table 2. SUS and the inferred heuristics scores of the models evaluated.

Parameter	**MBC**	**MBIC**	**MBEC**	All	Standard Deviation
SUS	86,50	82,05	79,24	81,90	3,07
Efficiency	89,17	83,04	79,71	83,06	4,02
Learnability	86,88	81,25	79,35	81,65	3,31
Memorability	87,50	78,57	82,61	81,85	3,80
Error Prevention	85,00	75,00	75,00	77,02	4,89
Satisfaction	81,67	75,30	76,09	76,61	3,03

Efficiency, with 83.04 compared to 79.71, and Learnability, with 81.25 compared to 79.71, suggesting that the MBIC is more efficient in task execution and easier to use compared to the model with an external controller. Conversely, the MBEC scored higher than the MBIC in two other metrics: Memorability, with 78.57 compared to 82.61, and Satisfaction, with 75.30 compared to 76.09, indicating that users found the version with an external controller easier to recall how to use after a period of non-use and reported greater satisfaction. There was a tie in Error Prevention, with both customized models achieving an identical score of 75 points, suggesting that the two models performed similarly in terms of their ability to prevent errors.

A notable contradiction is that, although the MBIC was rated most favorably by users in the initial preference questions, it received the lowest score in the SUS evaluation. In contrast, the MBC, which was the least preferred, achieved the highest SUS score and, consequently, higher ratings in usability heuristics. This discrepancy may be explained by the limited number of evaluations for the conventional model — only 10 assessments — where the smaller sample size influenced the final SUS scores. The technical usability assessment revealed that the conventional model was rated highest among those who evaluated it. These 10 evaluators, representing 16.4% of the total sample, appeared to favor simplicity over sophistication and customization, highlighting a divergence between subjective preference and measured usability in this context.

The perception of innovation and embedded technologies associated with the models with integrated and external control could have influenced the participants decision in the experiment. The MBC, being the original, simpler, and less interactive model, could have been perceived as less advanced or less interesting compared to the other models with controls, which may have contributed to its lower popularity and lower number of responses and public interest. Those who chose the MiritiBoard VR with integrated or external control may have been more attracted by the possibility of experimenting the artifact with new technologies and greater interactivity, which may have been more aligned with their interests or expectations, or stoked their curiosity about the customizations. The factors of embedded technology and novelty were not measured in the field tests, being only hypotheses raised by the authors.

The statistical analysis revealed a global mean score of 81.9 points, substantially above the average usability threshold (68), indicating an overall positive perception. The Shapiro–Wilk test showed that the data did not follow a normal distribution ($p = 0.0004$), leading to the adoption of non-parametric methods for group comparisons. The internal consistency of the scale was considered moderate, with a Cronbach's alpha coefficient ($\alpha = 0.639$) below the commonly recommended threshold of 0.70, suggesting that adjustments to certain items could improve the psychometric robustness of the instrument.

Group comparisons using the Kruskal–Wallis test revealed statistically significant differences in SUS scores among the three devices ($p < 0.05$), indicating that perceived usability varies depending on the configuration used. To detail this finding, a post-hoc analysis was necessary, and Dunn's test revealed that the performance of MBIC was significantly lower than that of MBC and MBEC. In contrast, no significant difference in usability was found between the MBC and MBEC configurations. This demonstrates that while the simple VR experience without controllers is superior to the integrated control, the addition of an external controller did not significantly alter the user's perception. Exploratory factor analysis confirmed the factorability of the data ($KMO = 0.754$; Bartlett $p < 0.001$) and, according to Kaiser's criterion, suggested the retention of three factors, with rotated (Varimax) factor loadings aligned with latent dimensions of effectiveness, efficiency, and satisfaction. Additionally, a k-means cluster analysis identified three distinct user profiles, with clear differences in mean SUS scores and heterogeneous distribution across devices, revealing relevant interaction patterns.

The comparison between groups using the Kruskal–Wallis test revealed statistically significant differences in SUS scores among the three devices, $\chi^2(2, N = 60) = 14.25, p = 0.001$. The median usability scores were 72.50 for MBIC, 85.00 for MBC, and 87.50 for MBEC.

To further explore this finding, a post-hoc analysis was conducted, and Dunn's test with Bonferroni correction showed that the performance of MBIC was significantly lower than that of MBC ($p = 0.003$) and MBEC ($p = 0.001$). Conversely, no significant difference in usability was found between the MBC and MBEC configurations ($p = 1.000$). This demonstrates that although the experience in simple VR without controllers outperformed that of the integrated controller, adding an external controller did not significantly change the user's perception.

The exploratory factor analysis confirmed the factorability of the data ($KMO = 0.754$; Bartlett's $p < 0.001$) and, according to Kaiser's criterion, suggested the retention of three factors, with rotated (Varimax) loadings aligned to latent dimensions of effectiveness, efficiency, and satisfaction. Additionally, a cluster analysis (k-means) identified three distinct user profiles, showing clear differences in mean SUS scores and a heterogeneous distribution across devices,

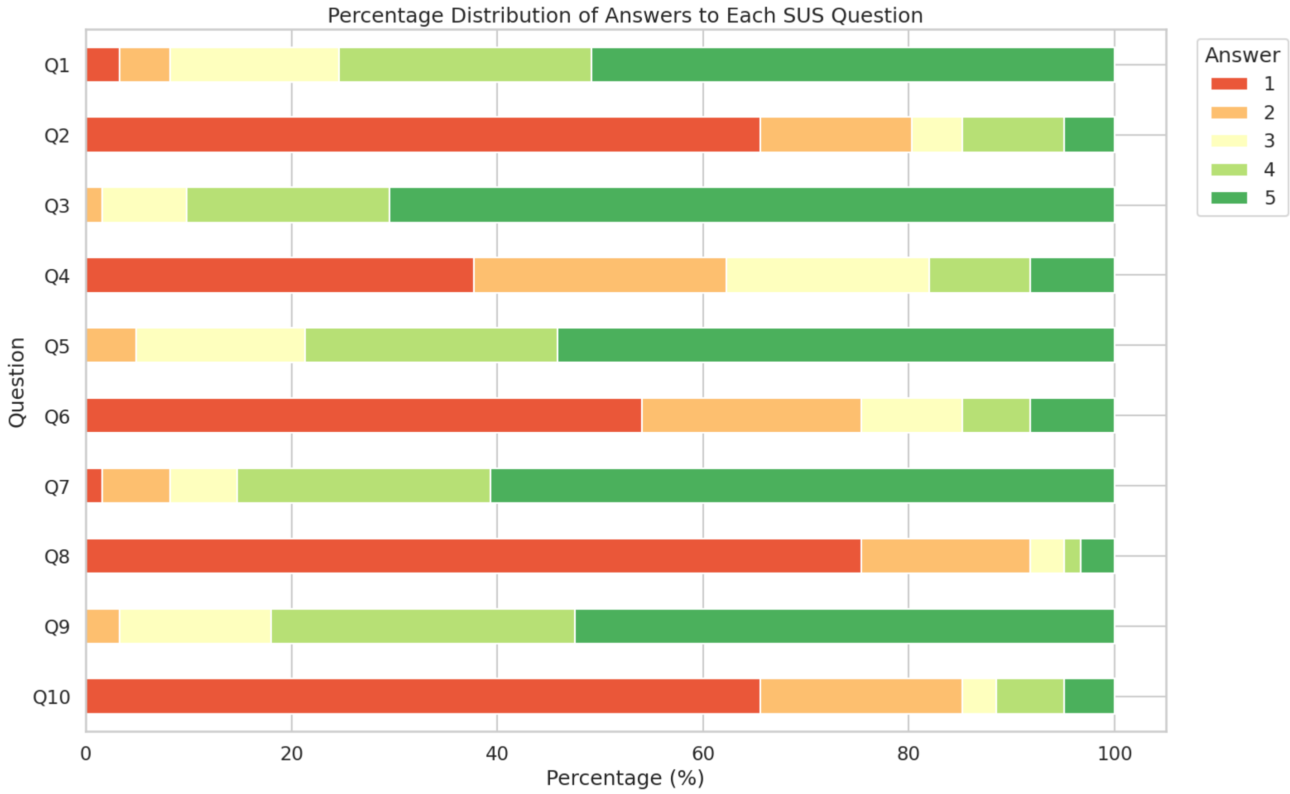


Figure 19. Percentage of answers for each item of the SUS questionnaire.

revealing relevant interaction patterns.

These results attest to the applicability of the SUS scale in the digital context and demonstrate how statistical and machine learning methods can deepen the understanding of user experience across different technological configurations. The discrepancy between evaluation scores and user preferences suggests that the innovation and new features of the prototypes, such as integrated and external controls, played a significant role in attracting users, even though these features were not rated as highly in terms of technical usability. This highlights the importance of balancing innovation with practical usability and considering user perception when developing and evaluating new prototypes.

7 Final Considerations

In this work, customizations and hardware adaptations were made to the MiritiBoard VR headset, with the addition of peripherals aimed at enhancing gameplay in AR and VR applications, particularly in the educational game GeoMeta, thereby investigating alternative interaction methods for a low-cost VR headset. The developed prototypes explore how these additional peripherals can enrich the user experience by comparing the classic version without adaptations, the prototyped version with controllers integrated into the headset (MBIC), and the version with an external controller (MBEC), in which the HMD is used with the addition of a GamePad.

Field tests were carried out, and user evaluations were collected through the SUS questionnaire, where, in addition to calculating the SUS scores of the models, five usability heuristics were inferred and quantified. Software modifications were implemented, including an open-world environment for convenient use of the prototypes equipped with controllers. In the experimental tests, participants first played the classic version of GeoMeta with the conventional MiritiBoard VR and then complementary versions of the MiritiBoard with integrated control and external control in the open world enriched with GeoMeta elements. After the experience, each user was invited to voluntarily and anonymously complete the usability questionnaire.

The results indicate that the addition of new peripherals to the MiritiBoard VR has the potential to transform how students interact with educational content, making the learning of geometry more dynamic and stimulating. The use of additional controllers with the headset enriches the VR experience, making it more immersive and comfortable. The classic version of the headset was also highly rated and well accepted by the public compared to the more sophisticated models with controllers, showing that, even as a low-cost headset, it is not inferior to more expensive models that inspired the adaptations made.

Future research is expected to deepen investigations into accessibility, with the goal of making GeoMeta even more inclusive for students with different disabilities. This includes developing specific features for learners with visual, auditory, or cognitive impairments through the integration of new sensors and peripherals, or by manufacturing the headset in other low-cost materials, such as pine wood or cardboard, ensuring that everyone can benefit from the application.

Among the work's limitations is that an ad-hoc Portuguese translation of the original English SUS questionnaire was used in the data collection. There were no cross-cultural and translation validations to assess whether this tool is valid for the scenario and object of the questionnaire's evaluation. The sample size was relatively small, with 63 respondents, and the group sampling involved several biases in the responses. There is no certainty as to which device a participant actually used or compared, so the SUS score they assigned to a specific model weakens the validity of the results. The connection between the user experience and the quantitative evaluation is weakened.

The chaotic environment of a public event can also introduce biases, such as fatigue or haste, affecting the quality of the responses. The potential impact of order effects, inherent to an uncontrolled field test, must be considered. For example, a participant who first tested the simpler MBC might have perceived the models with controls (MBIC and MBEC) as more innovative, influencing their preference. Conversely, a user who started with the complexity of the MBEC might have evaluated the simplicity of the MBC more favorably in terms of immediate usability, potentially inflating its SUS score. Although it is not possible to quantify these effects with the current data, acknowledging their existence is crucial to interpreting the discrepancy between the high preference for the MBIC and the higher usability score of the MBC.

Based on the lessons learned in this field study, future work will employ a controlled and counter-balanced experimental design. Participants will be randomly assigned to different device testing sequences (e.g., MBC -> MBIC -> MBEC; MBIC -> MBEC -> MBC, etc.) to neutralize order effects. Furthermore, data collection will be supervised to ensure each participant evaluates the correct device and that only those with comparative experience answer the preference questions, thereby ensuring the reliability and validity of the results.

Furthermore, among the group's future research directions, one highlight is the development of avatars based on Generative Artificial Intelligence (GAI), aimed at personalizing teaching, especially for neurodivergent students. In addition, the intention is to employ specific user experience instruments that evaluate the entire ecosystem, including the game's virtual environment. The SUS questionnaire was applied to assess the usability of the physical device, and therefore cannot provide much insight into immersion and engagement in the conducted evaluation, since SUS does not serve this purpose and lacks questions related to these aspects. An immersion assessment would evaluate characteristics of the virtual environment, not only the physical device in use, thus providing a more comprehensive picture of the player–game experience and the hardware and artifacts involved, as these are intertwined and inseparable elements of the user's experience.

Specific UX tools commonly applied to interactive products are expected to be used for user experience evaluation, such as AttrakDiff, User Experience Questionnaire, and Self-Assessment Manikin, as well as instruments targeting engagement, immersion, or flow, including the User Engagement Scale, Game Experience Questionnaire, Flow State Scale, and Player Experience of Need Satisfaction, which may also be investigated. It is worth highlighting the User Experience Questionnaire (UEQ), a survey consisting of 26 items organized into six main scales—each measuring a different aspect of the user experience—is considered a natural evolution of SUS in usability studies. Future work includes developing new prototypes with different user samples in controlled environments, aiming for more reliable and satisfactory results. The findings of this study demonstrate a broad field of research, with several gaps and nuances yet to be explored, offering fertile opportunities for future work.

Declarations

Acknowledgements

This work is an extension of the article "Integração de Periféricos no MiritiBoard VR: Análise de Usabilidade e Preferências" published in the Annals of the III Workshop on User Interaction and Research in Game Development (III WIPlay) [Oliveira Júnior *et al.*, 2024]. The authors express their gratitude to the JIS editorial team for the invitation to submit this extended version for publication and to Inteceleri for the partnership.

Funding

This work was carried out with the support of Coordenação de Aper- feiçoamento de Pessoal de Nível Superior (CAPES) – Financing Code 001; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPQ) through the processes 424515/2021-0 e 443482/2024-1 through the program Recursos Humanos em Áreas Estratégicas (RHAE); Financiadora de Estudos e Projetos (FINEP); Universidade Federal do Pará (UFPA); and Inteceleri Technology for Education.

Authors' Contributions

Flávio Moura contributed to the creation of the prototypes, MBIC and MBEC, the creation of the data collection form and the Python code to run the results in the collab. João Carvalho and Lucas Pereira were responsible for writing the text, reviewing the literature and analyzing the results. André Santos was responsible for creating the graph and pseudocode of the MBIC circuit. Waldemiro Negreiros was responsible for the statistical treatment of the data. Lyanh Lopes and Vinicius Neves were responsible for translating the manuscript. Walter Oliveira Jr was responsible for providing materials, and helping in logistical tasks. Diego Lisboa and Marcos Seruffo reviewed and corrected the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

The code for the microcontroller board on GitHub is available at the link `https://github.com/joaofmcarvalho/C-digo-Placa-ESP32/blob/main/esp32.cpp`. The form used to collect data can be accessed at the link `https://forms.gle/ixM5bn7RQVjfuqhu5`. The .CSV file with the form responses can be obtained from the link `https://docs.google.com/spreadsheets/d/1debQWHAuvuhIPTqt4HVVfj0_dJmYzcaLvxN_yhdBK8M/edit?usp=sharing`. The Python code used to generate the SUS score and Nielsen's heuristics can be accessed at the link `https://colab.research.google.com/drive/1_zmlfazzWPWzVnfg-8kXsx9_3nbxpwda?usp=sharing`. This availability enhances consultation, reproducibility, and, consequently, the principles of open science and knowledge sharing.

Further relevant information

This research was approved by an ethics committee under CAAE: 85196124.7.0000.0018 as detailed in section 5 about de ethical issues of the work. Artificial intelligence tools were used for textual revision and preliminary research of this study.

References

Agostinho, G. M. and Reis, V. M. S. d. (2024). Realidade aumentada como instrumento facilitador de aprendizagem sobre educação ambiental em turma do ensino médio integrado de meio ambiente do Instituto Federal Fluminense guarus. In *Anais do XVI Congresso de Iniciação Científica e Tecnológica e IX Congresso Fluminense de Pós-Graduação*, Campos dos Goytacazes, RJ. UENF.

Al-Ansi, A. M., Jaboob, M., Garad, A., and Al-Ansi, A. (2023). Analyzing augmented reality (AR) and virtual reality (VR) recent development in education. *Social Sciences & Humanities Open*, 8(1):100532. DOI: https://doi.org/10.1016/j.ssaho.2023.100532.

Amarante Jr, O. P. d., Sousa, E. O. F. d., and Brito, N. M. (2015). Percepção ambiental da população urbana próxima ao rio Buriti no município de São Bernardo, MA. *Pesquisa em Educação Ambiental*, 9(2):37–50. DOI: http://dx.doi.org/10.18675/2177-580X.vol9.n2.p37-50.

Ardiny, H. and Khanmirza, E. (2018). The role of AR and VR technologies in education developments: Opportunities and challenges. In *2018 6th RSI International Conference on Robotics and Mechatronics (IcRoM)*, pages 482–487. DOI: https://doi.org/10.1109/ICRoM.2018.8657615.

Barbosa, A. K. S. and Porfírio, R. N. d. S. (2021). Estruturas construídas com miriti e empregadas no ensino da química do DNA e RNA para estudantes do ensino médio de Belém-PA. Presented as poster in SEMANA NACIONAL DE CIÊNCIA E TECNOLOGIA DO AMAPÁ 2021, Macapá, 2021.

Batista, V. d. A., Bichara, C. N. C., Carneiro, C. R. d. O., Furtado, L. G., Botelho, M. G. L., Silva, D. F. d., and Pontes, A. N. (2021). Tecnologias sociais voltadas para o saneamento básico de comunidades ribeirinhas na amazônia. *Revista Brasileira de Gestão Ambiental e Sustentabilidade*, 8(19):909–920. DOI: https://doi.org/10.21438/rbgas(2021)081918.

Bogusevschi, D., Muntean, C., and Muntean, G.-M. (2020). Teaching and learning physics using 3D virtual learning environment: A case study of combined virtual reality and virtual laboratory in secondary school. *Journal of Computers in Mathematics and Science Teaching*, 39(1):5–18. DOI: https://doi.org/10.70725/297454nsjryb.

Boucinha, R. M. and Tarouco, L. M. R. (2013). Avaliação de ambiente virtual de aprendizagem com o uso do SUS - system usability scale. *RENOTE*, 11(3). DOI: https://doi.org/10.22456/1679-1916.44479.

Brito, S. d. S. and Medeiros, F. P. A. d. (2025). Desafios e oportunidades do metaverso na educação: Uma análise das funções cognitivas e implicações pedagógicas. *Revista Principia*, 62. DOI: https://doi.org/10.18265/2447-9187a2024id8432.

Brooke, J. (1996). SUS: A quick and dirty usability scale. In Jordan, P. W., Thomas, B., Weerdmeester, B. A., and McClelland, I. L., editors, *Usability Evaluation in Industry*, pages 189–194. Taylor & Francis, London.

Chiarini, T., Rapini, M. S., and Santos, E. G. d. (2024). Revelando tendências: análise dos resultados do censo dos grupos de pesquisa de 2023. Nota Técnica (Diset) 136, Instituto de Pesquisa Econômica Aplicada (Ipea), Brasília, DF.

Cochrane, T. (2016). Mobile VR in education: From the fringe to the mainstream. *International Journal of Mobile and Blended Learning (IJMBL)*, 8(4):44–60. DOI: https://doi.org/10.4018/IJMBL.2016100104.

Creed, C., Al-Kalbani, M., Theil, A., Sarcar, S., and Williams, I. (2024). Inclusive AR/VR: accessibility barriers for immersive technologies. *Universal Access in the Information Society*, 23(1):59–73. DOI: https://doi.org/10.1007/s10209-023-00969-0.

da Silva, L. G. P., Machado, R. C., da Silva, S. A. M., Dias, A. M., and Pires, P. A. (2023). O uso do metaverso na educação infantil: Oportunidades e desafios. *Cadernos da FUCAMP*, 22(56).

da Silva, L. M., Pontes, A., Batalha, S., and da Silva, L. (2013). Manifestação cultural no círio de Nazaré, Belém, Pará: A contribuição socioeconômica dos brinquedos de miriti na valorização do artesanato local. *Enciclopedia Biosfera*, 9(17):3584–3593.

de Souza, P. N., Guimarães, G. E., Junior, M. V., Berssanetti, F. T., and Filho, N. M. (2025). METODOLOGIA PARA AVALIAR NÍVEL DE MATURIDADE DA INDUSTRIA 4.0 E SUA CORRELAÇÃO COM ATRIBUTOS DO METAVERSO INDUSTRIAL. *ARACÊ*, 7(1):2817–2840. DOI: https://doi.org/10.56238/arev7n1-172.

dos Santos, A. M., Moura, F. R. T., Alves, A. V. N., Pinto, L. V. L., Costa, F. A. R., Oliveira Júnior, W. d. S., Cardoso, D. L., and Seruffo, M. C. d. R. (2023). Artificial intelligence in education 5.0: a methodology for three-dimensional geometric shape classification for an educational tool. In *2023 IEEE Latin American Conference on Computational Intelligence (LA-CCI)*, pages 1–6. DOI: https://doi.org/10.1109/LA-CCI58595.2023.10409430.

dos Santos, E. F. (2022). Gestos e jogos: reflexões e desenvolvimento de um sistema de detecção de gestos baseado em wearables para controle de jogos. Master's thesis, Pontifícia Universidade Católica de São Paulo. Available in: https://repositorio.pucsp.br/jspui/handle/handle/25768. Accessed: 8 January 2026.

Estevam, L., Oliveira Júnior, W., Silva, B., Bezerra, T., Cardoso, D., and Seruffo, M. (2024). Realidade virtual e aumentada no ensino de geometria: Um estudo de caso com GeoMeta. In *Anais do XXIII Simpósio Brasileiro de Jogos e Entretenimento Digital*, pages 1233–1244, Porto Alegre, RS, Brasil. SBC. DOI: https://doi.org/10.5753/sbgames.2024.241273.

Fabola, A., Miller, A., and Fawcett, R. (2015). Exploring the past with Google Cardboard. In *2015 Digital Heritage*, volume 1, pages 277–284. DOI: https://doi.org/10.1109/DigitalHeritage.2015.7413882.

Ferreira, A. L. and Silva, F. B. (2021). Universalização do acesso ao serviço público de energia elétrica no brasil: evolução recente e desafios para a amazônia legal. *Revista Brasileira de Energia*, 27(3):135–154. DOI: https://doi.org/10.47168/rbe.v27i3.645.

Ferreira Júnior, A. (2015). Entalhadores do efêmero: a vida associativa na criação dos brinquedos de miriti de Abaetetuba. Master's thesis, Universidade Federal do Pará, Pará, Brasil. Available in: http://repositorio.ufpa.br/jspui/handle/2011/10909. Accessed: Sept. 14, 2025.

Grier, R. A., Bangor, A., Kortum, P., and Peres, S. C. (2013). The system usability scale: Beyond standard usability testing. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 57(1):187–191. DOI: https://doi.org/10.1177/1541931213571042.

Guimarães, U. A., da Silva, F. M., and Silva, C. A. M. (2022). Metaverso na educação: oportunizando a inovação pedagógica. *RECIMA21-Revista Científica Multidisciplinar-ISSN 2675-6218*, 3(9):e391932–e391932. DOI: https://doi.org/10.47820/recima21.v3i9.1932.

Hazarika, A. and Rahmati, M. (2023). Towards an evolved immersive experience: Exploring 5g-and beyond-enabled ultra-low-latency communications for augmented and virtual reality. *Sensors*, 23(7):3682. DOI: https://doi.org/10.3390/s23073682.

Lee, J. M., Xia, X., Chua, F., Guan, Y., *et al*. (2020). Vego: A novel design towards customizable and adjustable head-mounted display for vr. *Virtual Reality & Intelligent Hardware*, 2(5):443–453. DOI: https://doi.org/10.1016/j.vrih.2020.09.001.

Lemes, D. d. O., Buesso Junior, J. C., and Rodrigues, J. J. F. (2024). Metaverso e educação: Um novo paradigma de aprendizagem? *RECIMA21-Revista Científica Multidisciplinar-ISSN 2675-6218*, 5(1). DOI: https://doi.org/10.47820/recima21.v5i1.4790.

Lourenço, D. F., Carmona Valentim, E., and Baena de Moraes Lopes, M. H. (2022). Traducción y adaptación transcultural de la system usability scale al portugués de brasil. *Aquichan*, 22(2):e2228. DOI: https://doi.org/10.5294/aqui.2022.22.2.8.

Mace, R. L. (1998). Universal design in housing. *Assistive Technology*, 10(1):21–28. PMID: 10181147. DOI: https://doi.org/10.1080/10400435.1998.10131957.

Maggiorini, D., Granato, M., Ripamonti, L., Marras, M., and Gadia, D. (2019). Evolution of game controllers: Toward the support of gamers with physical disabilities. In Holzinger, A., Silva, H., and Helfert, M., editors, *Computer-Human Interaction Research and Applications. CHIRA 2017*, volume 654 of *Communications in Computer and Information Science*. Springer, Cham. DOI: `https://doi.org/10.1007/978-3-030-32965-5_4`.

Mehrfard, A., Fotouhi, J., Taylor, G., Forster, T., Navab, N., and Fuerst, B. (2019). A comparative analysis of virtual reality head-mounted display systems. *arXiv preprint arXiv:1912.02913*. DOI: https://doi.org/10.48550/arXiv.1912.02913.

Moline, J. (1997). Virtual reality for health care: a survey. *Virtual reality in neuro-psycho-physiology*, pages 3–34.

Ng, A. W., Lo, H. W., and Chan, A. (2011). Measuring the usability of safety signs: A use of system usability scale (sus). In *proceedings of the International MultiConference of Engineers and Computer Scientists*, volume 2, pages 1296–1301. Citeseer.

Nielsen, J. (1994). Enhancing the explanatory power of usability heuristics. In *Proceedings of the ACM CHI'94 Conference on Human Factors in Computing Systems*, pages 152–158. DOI: https://dl.acm.org/doi/10.1145/191666.191729.

Nielsen, J. and Molich, R. (1990). Heuristic evaluation of user interfaces. In *Proceedings of the ACM CHI'90 Conference on Human Factors in Computing Systems*, pages 249–256. ACM. DOI: https://doi.org/10.1145/97243.97281.

Oliveira Júnior, W., Carvalho, J., Estevam, L., Seruffo, M., Alves, A., Pinto, L., Cardoso, D., and Pontes, P. (2024). Integração de periféricos no miritiboard vr: Análise de usabilidade e preferências. In *Anais do III Workshop sobre Interação e Pesquisa de Usuários no Desenvolvimento de Jogos*, pages 25–36, Porto Alegre, RS, Brasil. SBC. DOI: https://doi.org/10.5753/wiplay.2024.245480.

Oliveira Júnior, W., Estevam, L., Silva, B., Silva, J., Reis, M., and Seruffo, M. (2023). Geometa: Realidade virtual e aumentada no ensino de geometria. In *Anais do II Workshop sobre Interação e Pesquisa de Usuários no Desenvolvimento de Jogos*, pages 43–53, Porto Alegre, RS, Brasil. SBC. DOI: https://doi.org/10.5753/wiplay.2023.236289.

Oliveira Júnior, W. d. S. and Matos, C. A. d. (2019). Óculos ecológico de realidade virtual e seu respectivo processo de obtenção. Patente BR 102017015610-9 A2, Brasil. Data de Depósito: 18/07/2017; Data de Publicação Nacional: 19/03/2019.

Olson, J. L., Krum, D. M., Suma, E. A., and Bolas, M. (2011). A design for a smartphone-based head mounted display. In *2011 IEEE Virtual Reality Conference*, pages 233–234. DOI: https://doi.org/10.1109/VR.2011.5759484.

Othman, M. K., Nogoibaeva, A., Leong, L. S., and Barawi, M. H. (2022). Usability evaluation of a virtual reality smartphone app for a living museum. *Universal Access in the Information Society*, 21(4):995–1012. DOI: https://doi.org/10.1007/s10209-021-00820-4.

Papachristos, N. M., Vrellis, I., and Mikropoulos, T. A. (2017). A comparison between oculus rift and a low-cost smartphone vr headset: immersive user experience and learning. In *2017 IEEE 17th international conference on advanced learning technologies (ICALT)*, pages 477–481. IEEE. DOI: https://doi.org/10.1109/ICALT.2017.145.

Perla, R. and Hebbalaguppe, R. (2017). Google cardboard dates augmented reality: Issues, challenges and future opportunities. *arXiv preprint arXiv:1706.03851*. DOI: https://doi.org/10.48550/arXiv.1706.03851.

Persson, H., Åhman, H., Yngling, A. A., and Gulliksen, J. (2015). Universal design, inclusive design, accessible design, design for all: different concepts—one goal? on the concept of accessibility—historical, methodological and philosophical aspects. *Universal access in the information society*, 14:505–526. DOI: https://doi.org/10.1007/s10209-014-0358-z.

Ramaseri Chandra, A. N., El Jamiy, F., and Reza, H. (2022). A systematic survey on cybersickness in virtual environments. *Computers*, 11(4). DOI: https://doi.org/10.3390/computers11040051.

Santos, R. d. S. and Coelho-Ferreira, M. (2011). Artefatos de miriti (mauritia flexuosa l. f.) em abaetetuba, pará: da produção à comercialização. *Boletim do Museu Paraense Emílio Goeldi. Ciências Humanas*, 6:559–571. DOI: https://doi.org/10.1590/S1981-81222011000300006.

Silva, C. M. d. A. (2023). Um panorama recente do metaverso: revisão da literatura científica. Bachelor's thesis. Universidade Federal de Mato Grosso do Sul. Available in: https://repositorio.ifgoiano.edu.br/handle/prefix/3707. Accessed: 8 January 2026.

Smith, M. L., Spence, R., and Rashid, A. T. (2011). Mobile phones and expanding human capabilities. *Information Technologies & International Development*, 7(3):pp–77.

Torres, L. d. S. (2021). Experimentos de baixo custo para o ensino da física: uso do miriti como matéria prima. Bachelor's thesis. Universidade Federal do Pará. Available in: https://bdm.ufpa.br/jspui/handle/prefix/6586. Accessed: 8 January 2026.

Tranton, P. (2016). *Samsung Gear VR: An Easy Guide for Beginners*, volume 1. Conceptual Kings.

Vianna, P. H. F., Pereira, S. Y. L., Duarte, F. d. A., Teixeira, H. M. d. S., Morais, M. E. S., Costa, S. S. d., Costa, L. E. G., Amorim, W. M. d., Oliveira, L. d. S., and Pinheiro, C. C. B. (2024). O metaverso como ferramenta para educação sustentável: Desafios e oportunidades para os cumprimentos das ODS. In *Sustentabilidade, Tecnologia e Meio Ambiente: Tópicos Atuais em Pesquisa - Volume 4*, pages 56–67. Editora Científica Digital, Guarujá, SP. DOI: https://dx.doi.org/10.37885/241118272.

Vieira, I. R. (2017). *Percepção ambiental, uso, manejo e valoração econômica da palmeira Buriti (Mauritia flexuosa L.f.) na região dos Lençóis Maranhenses, Brasil*. Tese de doutorado, Universidade Federal do Piauí. Available in: `http://repositorio.ufpi.br/xmlui/handle/123456789/564`. Accessed: Sept. 14, 2025.

Wahyuningrum, T., Kartiko, C., and Wardhana, A. C. (2020). Exploring e-commerce usability by heuristic evaluation as a compelement of system usability scale. In *2020 International Conference on Advancement in Data Science, E-learning and Information Systems (ICADEIS)*, pages 1–5. DOI: https://doi.org/10.1109/ICADEIS49811.2020.9277343.

Yeung, A. W. K., Tosevska, A., Klager, E., Eibensteiner, F., Laxar, D., Stoyanov, J., Glisic, M., Zeiner, S., Kulnik, S. T., Crutzen, R., *et al*. (2021). Virtual and augmented reality applications in medicine: analysis of the scientific literature. *Journal of medical internet research*, 23(2):e25499. DOI: https://doi.org/10.2196/25499.

Zhao, X., Ren, Y., and Cheah, K. S. (2023). Leading virtual reality (vr) and augmented reality (ar) in education: bibliometric and content analysis from the web of science (2018–2022). *SAGE Open*, 13(3):21582440231190821. DOI: https://doi.org/10.1177/21582440231190821.