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Article

Towards an Accessible Metaverse Experience: Evaluation of a Multiplatform Technological Heritage Museum Prototype

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Abstract: Before metaverse technologies become fully integrated into daily life, their accessibility must be carefully considered. To ensure equal opportunities for all users, regardless of age or disability, immersive technologies should offer seamless and intuitive interaction with virtual environments, objects, and other users. This paper presents an evaluation of the accessibility and user experience of a metaverse technological heritage museum prototype on two platforms: mobile devices and virtual reality. Through feedback from 64 participants of various ages, we define accessibility guidelines for metaverse museums and identify requirements for improving the prototype. Our findings reveal significant differences between young participants and adults in their navigation and interaction experiences across platforms. This work addresses a research gap in metaverse museum accessibility evaluation and contributes to the development of more inclusive virtual spaces by providing concrete recommendations aligned with accessibility standards.

Keywords: metaverse museum; technological heritage; accessibility; inclusion; universal design; evaluation; guidelines; virtual reality; mobile device; user experience

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1. Introduction

Although the term *Metaverse* originates from 1992 when Stephenson mentioned it in a context where avatars, people's audio-visual representations, communicate with each other [1], it was not until recent years that this concept attracted considerable attention. In 2021, Zuckerberg announced the metaverse as a new, more immersive platform—an embodied internet where the user is immersed in the experience [2]. That is the point when virtual reality became widely recognized as the gateway to the metaverse [3]. Virtual reality technology and virtual environments can be defined as "a computer generated display that allows or compels the user (or users) to have a sense of being present in an environment other than the one they are actually in, and to interact with that environment" [4]. The development of virtual worlds, i.e., virtual environments in which people can interact with each other, such as Second Life [5], popular games such as VRChat [6] or game creation platforms such as Roblox [7], all contributed to building components for the metaverse. Roblox is one of the most famous platforms of the metaverse whose majority of users are children, so it is important to understand how to maximize the benefits that the metaverse can bring to the users. The research findings from the overview of studies on learning in Roblox indicate that, when used as a learning environment in the metaverse, it can be beneficial in three main ways: socialized teaching, learning environments supported by virtual reality, and programming for STEM education [8].

Learning in a virtual reality environment offers high flexibility in terms of different virtual scenarios and events that can be recreated which are usually impossible to visualize in a physical classroom given the different distance, safety, or time factors. Since virtual reality and other immersive technologies, such as augmented and mixed reality, are considered one of the technological pillars upon which the metaverse is built [9], it is not surprising that research trends in recent years show that the metaverse also has potential in the domain of education. The results of the literature review in [10] show that there is a motivation for using the metaverse in education fields such as natural science, mathematics and engineering, as well as in general education, because of the benefits it can bring to the learner. However, it has been found that there is a necessity for more research focusing on how to develop an accessible and inclusive metaverse since no study has been found on using the metaverse in education for students with disabilities [10]. Accessibility is defined as a measure of the extent to which products, systems, services, environments, and facilities can be used by people from a population with the widest range of users [11]. According to [9], the metaverse will be integrated into people's daily lives and widely applied in various fields, such as the game industry, remote work, travel and tourism, education, culture and entertainment, and socialisation. This makes it even more important to consider the accessibility of metaverse technologies so that different users, including people with disabilities and the elderly, can access it on various platforms.

Digital inclusion should be one of the priorities when developing components of the metaverse in the context of immersion and interaction in virtual environments. One of the goals of digital inclusion is to make mainstream immersive content inclusive for a broad user base. That means that all mainstream application areas of XR technology should ensure inclusion. XR technology is an umbrella term for a variety of digital reality formats, including virtual reality (VR), augmented reality (AR) and mixed reality (MR). Although XR technology is still in its early stages and not widely adopted, as a vital component of the metaverse [9], XR technology needs to provide a seamless and intuitive way to interact with the virtual world, objects, and other users, no matter their age or disabilities. Ensuring equal and equitable access to mainstream XR applications is an ethical priority so that a wide range of users can benefit from them [12]. One of the mainstream application areas that should adhere to these ethical requirements is certainly museums, which have an educational purpose in addition to exhibiting art, science, technology and other subjects. XR technologies can enhance museum visits in different ways, whether to enrich the visitors' experience with the augmentations that AR brings or to provide distance access to exhibitions with VR, especially for people who cannot visit the museum themselves. The benefits for the younger users of metaverse museums are also recognized, as they are keen on using emerging technologies. The metaverse museum provides a way to enrich young people's experiences when learning about cultural heritage [13]. Related to that, different factors influencing their continued use of metaverse museums are being researched [14].

The authors in [15] evaluated how existing metaverse platforms and tools, such as Spatial.io and Meta's Horizon Worlds, meet the requirements necessary to have a functional metaverse ecosystem that aligns with existing literature and industry standards, one of them being accessibility. Their findings show that accessibility criteria are addressed in different ways across various platforms and that metaverse platforms must prioritize the implementation of accessibility measures to create a universally inclusive environment [15]. Many studies have investigated the need to address a lot of open questions related to designing and evaluating an inclusive, accessible, and safe metaverse that guarantees equity and diversity, e.g., refs. [16,17]. Both studies are based on expert opinions and analysis of existing platforms and technologies. However, in future research efforts, the focus must be put on collecting and analysing experiences from individuals with diverse needs to create a metaverse with equal opportunities for all individuals.

Given the above, we have been motivated to put more effort into exploring the possibilities of currently available metaverse platforms and their support for ensuring an accessible metaverse for everyone, as well as identifying the best approaches to evaluating the accessibility of the metaverse environment on different platforms. Our work focuses on evaluating a technological heritage museum within the metaverse, specifically analysing its accessibility and user experience. User experience is defined as users' perceptions and responses that result from the use and/or anticipated use of a system, product or service [11]. By evaluating accessibility challenges, we aim to provide insights into improving the metaverse museum experience and making it more inclusive, and by evaluating user experience, we aim to gain insight into the differences in metaverse experiences on different platforms as well as how to make the metaverse museum more attractive to users.

Our study explores how different user groups, particularly young participants and adults, navigate and interact with the virtual museum on mobile devices and in VR. Through user testing and feedback analysis, we aim to identify accessibility challenges faced by different age groups, compare user experience of a metaverse museum between mobile and VR platforms, define requirements for improving the metaverse museum prototype and contribute to the development of accessibility guidelines for metaverse-based museums.

Given this work's objective, we can define the following research questions (RQs):

- RQ1: Are there any differences between different age groups in terms of accessibility of the metaverse museum on mobile and VR platforms?
- RQ2: Are there any differences in user satisfaction with the metaverse museum on two different platforms (mobile device and VR)?
- RQ3: What design recommendations can improve the accessibility and inclusivity of metaverse museums?

The sections of this paper are organized as follows. Section 2 introduces the topic of accessibility in the metaverse and museums in the metaverse. In Section 3, we describe the materials and methods used for the study. Section 4 presents the results and feedback analysis. Section 5 brings a discussion of the results, limitations of the study and future work. The conclusion is described in Section 6.

2. Literature Review and Related Work

2.1. Accessibility in the Metaverse

2.1.1. User Needs and Accessibility Barriers

To start addressing the core challenges related to accessibility in the metaverse, it is necessary to understand different user needs and the accessibility barriers in immersive experiences. It is important that users, regardless of their abilities, disabilities or age, are not excluded from new social environments and have equal access to all the opportunities that immersion in the metaverse brings. According to the survey results described in [18] including 101 participants with a broad range of access difficulties, even those with prior experience with immersive technologies encountered some access barriers that affected their enjoyment or even forced them to stop the experience. The key barriers in immersive technologies faced by users living with a range of impairments, i.e., physical, visual, auditory, and cognitive, are identified by the authors in [19] and grouped into four core themes: software usability, hardware usability, ethics, and collaboration/interaction. Besides trying to understand different user needs before developing an AR/VR product, it is necessary to include representatives of end users in all stages of product development to inform decisions that maximise usability for as broad a population as possible [20].

According to [21], the focus of current metaverse projects is not on the application of methods to understand user needs but rather on the projects themselves. To improve accessibility and inclusivity in the metaverse, the inclusion of users with disabilities should always come first, even before the technology [21]. By applying universal design principles, we can ensure that the diverse needs and requirements of users in the metaverse are met. These two aspects (application of universal design principles and inclusion of users with disabilities) are highlighted as one of the key requirements for enhancing accessibility and inclusivity in the Metaverse in [21]. Removing many barriers to accessibility of immersive technologies can also have a positive impact on non-disabled users, as they face some of the same issues, e.g., discomfort with head-mounted displays, eyestrain or risk of physical injury [19]. Users who are temporarily or situationally disabled can also benefit from inclusive design or different accessibility options.

In addition, users who can benefit from the social aspect of the metaverse are older adults since social VR experiences and applications show great potential for older users [20,22]. According to a study described in [23], one of the benefits could be the positive effect on their self-confidence and self-imposed isolation. Their needs should also be investigated in the aspect of cognitive abilities which often decline with age. Accessibility of metaverse technologies for people with mild cognitive impairment and dementia is assessed in [24], and the authors' findings present a good starting point when designing metaverse applications for all. However, all recommendations should be used and evaluated with users in experimental studies, which is a further step towards creating more standardized guidelines.

Another aspect of accessibility that is important to be considered in the metaverse is related to avatar diversity and the self-presentation of people with disabilities. According to research in [25], many people with disabilities are willing to disclose their disability through avatar design. Although some social VR platforms offer avatar customization, there is limited diversity support for people with disabilities [25]. The same research revealed concerns about the potential risks caused by disability disclosure in social VR using avatars (e.g., cyber-bullying) [25], while research described in [26] revealed that, despite the harassment, users with disabilities are willing to continue using avatars with disability disclosure. That is why it is also important to ensure guidelines for the design of a safe and inclusive metaverse environment.

2.1.2. Accessibility Guidelines and Tools

Among three critical challenges for user experience in the metaverse, the authors in [27] highlight interoperability, scalable awareness and accessibility. Although these challenges, which are crucial for the practical development of user-friendly metaverse systems, are considered overlooked in current standard discussions (according to [27]), we can see that awareness about them has been raised. For example, there is a Metaverse Standards Forum working group [28] dedicated to securing accessibility and inclusion for everyone in the metaverse. One of their goals is also to support the creation of comprehensive XR standards on par with the Web Content Accessibility Guidelines 2.2 (WCAG) [29]. In addition, the International Telecommunication Union (ITU) suggested recommendations for aligning metaverse platforms with sustainable development goals based on digital transformation by addressing the user experience (UX) design dimensions of the platforms [30]. In their report [30], the authors emphasize that accessibility should serve as a means for realizing inclusion in developing metaverse, so their recommendations can be considered as one step closer to developing a set of guidelines for assessing inclusion and accessibility in the metaverse. However, while there is a big gap between the regulations for web accessibility and XR, there is still a lack of a comprehensive and widely acknowledged set of accessibility guidelines for VR games and XR technologies in general [24,31].

As VR is considered one of the metaverse's technological pillars, it is worth investigating the state of different accessibility guidelines for VR games that can be applied to metaverse applications. The authors in [31] synthesized guidelines from different sources to identify the relevant ones for accessible VR games. Their resulting set of guidelines is based on literature research only, so further empirical research with users is necessary to address accessibility needs that have yet to be identified in the field [31]. Besides many calls for joint initiatives toward proposing more formal guidelines for the development of accessible VR solutions, there is also a recognized need for a more standardized method of rating the comfort, accessibility, and safety of publicly available VR applications [32].

While the standards for defining accessibility in XR are sorely lacking, there are efforts to improve accessibility in VR, AR and the metaverse. A good example of accessibility guidelines for VR developers to follow is Meta's guidelines on designing accessible VR [33] for their Meta Quest VR platform. Also, accessibility features are gradually being introduced to VR platforms [34]. An extensive overview of research and commercial efforts aimed at improving the accessibility of VR and AR from [20] resulted in a set of emerging strategies for maximizing the inclusiveness of VR and AR applications. The performed review also resulted in highlighting the next three challenges to achieving "inclusive immersion": (i) diversity in user needs; (ii) lack of guidance and tools for developers; and (iii) difficulty in conducting empirical research, which also calls for more efforts from the research community in this domain [20]. While the research and understanding of immersive technology grows, researchers must come together and utilize existing knowledge to create a truly inclusive and accessible metaverse for people with diverse needs [34].

Although the commercial efforts to improve the accessibility of VR hardware and applications are growing, it would be even more beneficial if proven systems and solutions were packaged into toolkits or downloadable assets to assist developers in the endeavour toward a more accessible metaverse experience [20]. As noted in [27], addressing some of the forms of accessibility by sharing content, e.g., in the forms of tools and packages, can also facilitate the management of interoperability between clients, addressing interoperability as one of the acknowledged challenges of the metaverse. An example of an open-source package for adding accessibility features to XR games and interactive experiences is the Accessibility Toolkit for Unity [35], a multi-platform game engine also used for developing immersive XR environments. The toolkit creates context-aware subtitles for VR/AR projects for people with hearing impairments, which can also benefit internationalization and non-fluent speakers [35]. Another example is SeeingVR, presented in [36], which is a set of 14 low-vision tools that can be applied to VR applications. Both approaches to applying SeeingVR (a plugin with nine tools that augments an existing VR application without developer effort, and a Unity toolkit that allows developers to provide the metadata required to integrate all 14 tools during development) are examples of best practices in making the effort to improve the accessibility of mainstream VR for people with low vision [36].

2.1.3. Existing Solutions with Universal Design Approach

While research related to developing and evaluating specialised solutions and environments for people with specific disability is valuable, users with diverse needs would benefit much more if more effort were invested in making mainstream applications and environments accessible. This is especially important for immersive environments in the metaverse since one of their objectives is to be able to socialise in virtual space while using new forms of human–computer interaction. In this context, blind and low vision (BLV) users may encounter continued accessibility barriers if there is no way to support their access needs. According to [37], only a few researchers have examined mainstream VR, creating methods and tools for VR developers to integrate accessibility into their applications (one of them mentioned earlier—SeeingVR). However, most of that work is based on the single-user VR experience, implying that more research should be put into investigating different accessibility measures for more complex multiuser experiences [37]. One such attempt to address BLV user needs in social VR is described in [37], where they proposed a solution based on the real world's approach, i.e., a sighted guide to support a BLV user with navigation and visual interpretation in an unfamiliar environment, i.e., a virtual space. An example of how a virtual world can be made more accessible for people with a range of perceptual, physical and cognitive disabilities is described in [38]. PowerUp is a multiplayer educational game with a wide range of accessibility features [38]. Although they have identified the main accessibility features for 2D and 3D elements in virtual worlds in their study [38], several aspects that are important for an accessible metaverse have not been considered, such as the accessibility requirements when using different access platforms, e.g., mobile devices or head-mounted displays, or considering the social aspect of the metaverse and investigating accessibility barriers when interacting with other users.

Apart from solutions that include certain accessibility options, to the best of our knowledge, there are still no solutions that comply with the principles of universal design intending to be accessible to as many users as possible. Whilst there are efforts to make XR solutions, including social VR, more accessible to certain user groups, there is not yet sufficient awareness among developers of the importance of making the metaverse accessible from the early stages of development.

2.2. Museums in the Metaverse

The research related to virtual museums based on XR technology has grown since the COVID-19 pandemic occurred as real museums stopped receiving visitors [39]. Because of the positive effects that virtual visits can bring to tourists, XR technology proves to be useful when museums are closed to the public [40]. These new interactive experiences that XR technology brings into museum exhibitions open numerous possibilities, even for greater inclusivity and diversity [39].

However, the development of such museum experiences is not straightforward. The authors in [41] emphasize that besides technology, the focus of research should be directed towards the conditions and content. Their study [41] examined how the use of multilayer animations and sophisticated shader technologies within metaverse platforms impact user engagement, immersion, and overall experience. Some virtual museums in the metaverse are already available online, e.g., The Replica [42], which is a virtual replica of The Metropolitan Museum of Art on Roblox or the Vordun Museum [43] available in Second Life. However, some research aspects still need to be explored in the future, such as the creation of personalised metaverse museum tours based on user interests [44]. One of the aspects that should be addressed with greater priority is the accessibility of metaverse museums. A case study described in [45] investigated different aspects of the virtual experience of the Museo dell'Artigianato Valdostano museum implemented in the metaverse. Those aspects included perceived realism, engagement, immersion, control of the virtual environment, and auditory and visual quality, while accessibility is only mentioned in relation to the availability of the museum experience to a wider audience [45]. When we talk about accessibility for a wider audience, we should think about basing the metaverse museums on the principles of universal design, as this will enable authentic learning environments that are accessible to everyone [46].

The study in [47] explored how the needs of people with impairments can be facilitated by XR technologies when visiting a museum. Most of the XR-based solutions in museum-related research for people with different impairments are focused on one type of impairment, meaning that a more universal approach is needed so that the museum experience can be adapted to the individual needs of a person [47]. A pilot study described in [48] utilized a user-centred design approach where children and people with disabilities participated in the co-design of the virtual experience to ensure an accessible and inclusive virtual museum. The results they presented in the form of the virtual museum features can serve as guidelines for improving the accessibility of immersive virtual environments [48]; however, the usefulness of the proposed features should be evaluated with a broader range of people with different disabilities and ages, especially elderly people.

There are more studies related to museums in the metaverse, such as Spatial's IES Goya Museum [14], a Kunqu Metaverse virtual museum [49], a virtual museum with a cultural heritage piece from the Local Historical Museum of Montilla [50], and the Farewell Museum's metaverse exhibition [51]. However, they do not touch upon an accessibility evaluation.

2.3. Summary

To provide a consolidated overview of the research conducted to date, Table 1 summarizes key themes identified in the literature related to accessibility in the metaverse. This includes the focus areas, key findings, identified research gaps, and associated sources. The table serves as a quick reference to the current state of the art and highlights directions for future work, particularly in addressing the needs of users with diverse needs, the development of universal design approaches, and the accessibility of immersive museum experiences.

Table 1. Summary of key themes and findings from the literature on accessibility in the metaverse.

Theme	Focus	Key Findings	Gaps/Future Work	Sources
Accessibility in the Metaverse	User needs and barriers	Users with disabilities face barriers even with experience in XR; key barriers related to software/hardware usability, ethics, and interaction	Need to include users in design process; more empirical research needed	[18–21]
	Inclusive design principles	Universal design and early inclusion of users with disabilities improve accessibility for all	Cognitive aspects underexplored; more age-inclusive studies needed	[20,21,24]
	Older adults in social VR	Potential benefits for well-being, confidence, and social engagement	Cognitive aspects underexplored; more age-inclusive studies needed	[22–24]
	Avatar diversity and identity	Desire to disclose disability via avatars, despite risks of cyberbullying	Need guidelines for safe and inclusive metaverse spaces	[25,26]

Table 1. *Cont.*

Theme	Focus	Key Findings	Gaps/Future Work	Sources
Accessibility Guidelines and Tools	Standardization efforts	Growing awareness about accessibility; WCAG-inspired goals by Metaverse Standards Forum; ITU's recommendations for inclusive and accessible metaverse	No regulations for XR accessibility; lack of comprehensive XR accessibility guidelines and a standardized method for rating publicly available VR applications	[27–32]
	Development guidelines and challenges	Guidelines based on literature research; Meta's guidelines; accessibility features gradually introduced to VR platforms; diversity in user needs as a challenge	Lack of empirical validation	[20,31,33,34]
	Development tools and assets	Unity Accessibility Toolkit, SeeingVR, examples of best practices	Need for more developer support; lack of tools for developers	[20,27,35–37]
Universal Design in XR	Mainstream solutions	Efforts of solutions with accessibility options (like PowerUp) and social VR adaptations (e.g., sighted guide approach)	Limited focus on accessibility for different platforms and the social aspect of the metaverse	[37,38]
Museums in the Metaverse	Virtual museums use cases	XR brings new opportunities after COVID-19; XR brings possibilities for greater inclusivity and diversity	Limited or no focus on accessibility in museum design and evaluation	[14,39–43,49–51]
	Accessibility in virtual museums	Some user-centered studies; co-design with children and people with disabilities show promise; emphasis on universal design as a foundation for inclusive learning	Evaluation with a broader range of people needed; need for a personalized metaverse museum based on universal design principles	[44,46–48]

To summarize, recent studies highlight a significant lack of case studies and practical implementations that address accessibility challenges in the metaverse [10,17]. Our study addresses this gap by presenting a real-world application, i.e., a metaverse technological heritage museum, designed to investigate and better understand the accessibility barriers users encounter in such virtual environments. To help harness the full potential of metaverse-based digitalization in cultural heritage preservation, different aspects related to metaverse technologies and virtual heritage experiences should be further investigated, as emphasized in a recent study from [52]. Some of the recommendations from [52] are to explore the use of immersive technologies for interacting with cultural heritage to enhance the user experience as well as to investigate current concerns in virtual heritage experiences, such as accessibility and inclusivity, which are the areas our work is focusing on.

A recent study related to the cultural heritage preservation in the metaverse pointed out that investigating the impact of different user demographics on their experience and interaction with XR technologies could provide deeper insights into how to tailor applications for diverse audiences [53]. Having said that, a key novelty of our research lies in its focus on gathering and analysing feedback from users of varying ages during the early development stages. This user-centred approach enables us to uncover age-specific needs and accessibility concerns that are often overlooked in the current literature. By doing so, we aim to inform the development of concrete guidelines and best practices for enhancing accessibility in diverse platforms for the metaverse, especially across diverse age groups, a gap also noted in recent research [17,20].

While a fully accessible metaverse experience remains unattainable with current technologies, due to persistent barriers in virtual and augmented reality, particularly for users with disabilities, our study represents an important step toward addressing this challenge [15,21]. It provides empirical insights and practical directions for future development, contributing to the broader discourse on inclusive design in emerging digital environments.

3. Materials and Methods

3.1. Development of the Virtual Museum Prototype for the Metaverse

The virtual museum prototype was developed as a result of a final degree project by P. Tamarit Núñez [54]. The virtual environment was developed in the Unity game engine version 2021.3.44f [55] and adapted to support migration to the metaverse using the Spatial platform [56]. It includes different artefacts that are part of the Vicente Miralles Segarra Telecommunication Museum, located in the Escuela Técnica Superior de Ingeniería de Telecomunicación (ETSIT) of the Universitat Politècnica de València (UPV), Spain [57]. The artefacts in the virtual environment are virtual representations of objects or videos of the abovementioned museum related to telephony, either through communication, its evolution or its history.

The development of the virtual museum prototype included the following activities: specification of artefacts to include in the virtual museum and in which form they will be presented (e.g., image, 3D objects, video), collection of the artefacts in the specified file format (by taking photographs of the objects, scanning them or recovering files from projects previously carried out on the museum), selection of the technology for developing the virtual environment as well as the platform for project migration to the metaverse, implementation of the virtual museum and ensuring compatibility with the Meta Quest 3 virtual reality headset (a product by Meta Platforms, Inc., a company from Menlo Park, CA, USA). ETSIT UPV provided the devices for developing and evaluating the virtual museum.

Previous research related to the Vicente Miralles Segarra Museum of Telecommunications investigated how augmented reality enhanced the visitor experience in the museum [58]. As part of the mentioned research, a virtual reality application was developed in Unity that replicates the entire museum in a virtual environment. However, the Unity project with the VR application was not compatible with migration to the selected metaverse platform, i.e., Spatial, which is a gaming platform by the homonymous company based in New York, NY, USA. To publish a Unity project to Spatial, a specific template in Unity must be used as well as a specific Unity version that does not match the previous VR project. Therefore, the development-from-scratch approach was applied.

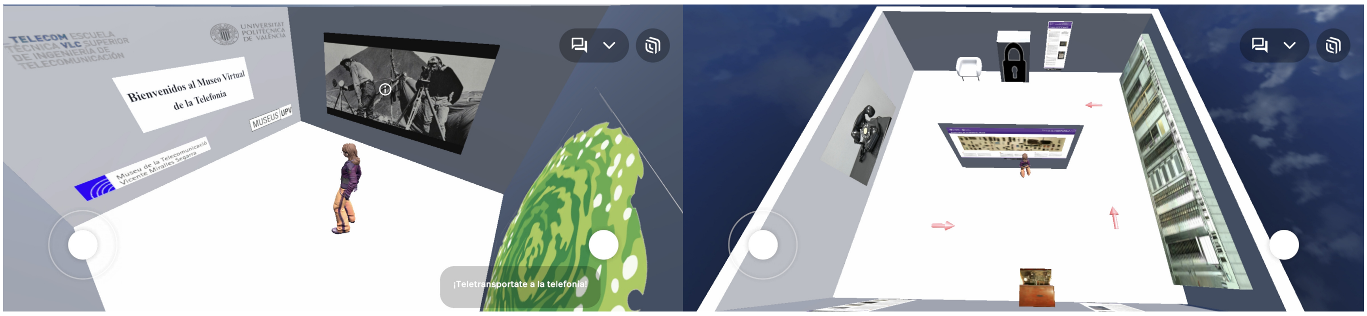
The advantage of metaverse platforms like Spatial is that they allow access from any place and on different platforms, thus increasing the availability of metaverse spaces for many users. The Spatial Creator Toolkit is a toolkit for Unity that allows the creation and publishing of projects to run with Spatial on the Web, iOS, Android, and VR platforms with no additional configuration [59]. The prerequisite is to use a specific Unity version that supports this toolkit and to have the WebGL Build Support module installed. The Spatial

Creator Toolkit includes a template for Unity that offers free upload of created spaces to the metaverse in Spatial cloud servers. The Spatial platform allows the modification of certain things in space after uploading, which allows the projects to be updated. For example, it is possible to add elements such as videos, images, documents and 3D models later in the space.

For the efficient and cost-effective creation of 3D models for the virtual museum, an iPhone 15 Pro device equipped with a LiDAR (Light Detection and Ranging) scanner was used. An iOS application, i.e., Polycam 3D Scanner [60], was used to export scanned models directly to Sketchfab [61]. Then, 3D models were directly imported from Sketchfab to the virtual museum in Spatial.

3.1.1. Virtual Museum Structure and Content

The virtual museum environment consists of two rooms with different artefacts that users can observe and interact with. The first room is a square-shaped room where the visitor is given a context about the museum, establishing what this space is about. In addition, this room also serves as a welcome space where the user gets familiarised with the navigation and interaction controls before it is displayed with the museum artefacts. The exhibition room is rectangular (6.5 m long and 6 m wide) with a long wall in the centre, giving it a sense of circulation and separating the room into zones. Figure 1 shows both rooms from a distance.



(**a**) (**b**)

Figure 1. Virtual museum rooms: (**a**) welcome room with information about the room; (**b**) exhibition room with exposed museum artefacts (the arrows on the floor indicate the direction of the museum visit). Screenshots were made on the mobile device.

The elements selected for the exhibition in the virtual museum and that can be found in the exhibition room are:

- Women telephone operators: Depiction of the evolution of women who worked in the telephone service from 1890 to 1980.
- Manual switchboard: In the early days of telephony, communication was established by connecting two point-to-point devices using private lines. This process was carried out manually in these switchboards by inserting a metal pin into the holes at the crossing point.
- The evolution of cellular telephony: Display of mobile phones from the first 4 generations, starting in 1973 with the first portable prototype and ending with 4G mobile phones from 2014.
- Rotary: The evolution of the manual switchboard. Using electronic switching, it was able to manage up to 10,000 lines. They were very large switchboards that took up a lot of space, reaching up to 5 m in height.

- Pentomat: The evolution of switchboards. It was an electromechanical automatic switching device. It was a Spanish technological development and one of its distinguishing features was the ability to hold incoming calls.
- Evolution of telephones: Depiction of a timeline from 1910 in which various types of telephones are shown, from wall and table phones to mobile phones.
- Elements selected for exhibition in the virtual museum are physically located in the Vicente Miralles Segarra Telecommunications Museum, except for the Rotary due to its large size. Additionally, several videos and images are added to the virtual museum.

3.1.2. Spatial Components and Features

Since Spatial supports just a subset of C# and the Unity engine codebase, it is not easy to implement custom functionality for Spatial space. Thus, the virtual museum prototype utilizes Spatial's components for building the experience related to the interaction with elements or the avatar, such as *entrance point*, *interactable*, *point of interest*, *avatar teleporter* and *empty frame* [59].

The *entrance point* specifies an area where avatars will be placed when entering the space. In the virtual museum, the avatars are placed in the middle of the welcome room facing towards the wall with the welcome sign as well as the logos related to the UPV, ETSIT, UPV museums and Vicente Miralles Segarra Museum of Telecommunications. In this room, a video is set up on the adjacent wall on the right. It is a 50 s video with introductory information about the museum. To attract visitors' attention to this video, a *point of interest* is used. That is a location marker with the display of additional information when the user approaches a specific location. Figure 2a shows a *point of interest* used for this video when the avatar approaches. While the *point of interest* is configured in Unity, the video itself is inserted in Spatial. To proceed to the exhibition room after the user has been familiarized with the space, the *avatar teleporter* component has been used which teleports the avatar to a target location after entering the trigger area. A *point of interest* is added to the portal used for teleportation to invite visitors to teleport.

(**a**) (**b**)

Figure 2. The use of Spatial components: (**a**) *point of interest* component showing additional information to attract the user; (**b**) *interactable* component on the button displaying the year to select.

Once the user has entered the exhibition room, they will find all the elements selected for the exhibition and described in the previous subsection. The direction of the tour through the room determines that the visitor first visits the evolution of the telephone operators. An *interactable* component has been inserted between the poster about the telephone operators and the manual switchboard object to give this element an interactive character. By pressing the buttons displaying the years from 1890 to 1980, an image of the telephone operator from that year is displayed next to the switchboard. For the button objects, an *interactable* component was used that triggers an event, i.e., the display of the image after the user has interacted with it. The buttons are displayed depending on the proximity of the user. Figure 2b shows an image of the telephone operator after selecting one of the interactable buttons with the displayed year.

The manual switchboard object is created by modelling each part of the switchboard separately and assigning a material with the corresponding shader to each of the areas. A *point of interest* component is also used for this element to display its labelling when the user approaches it. To the left of the manual switchboard, there is a poster about telephone switching. In the same passage of the room, on the interior wall, there is a poster with descriptions and photographs related to the evolution of cellular telephony. While the part of the poster with photographs was added in Unity, other elements, such as the poster title and text descriptions in different languages, were added in Spatial. Moving on with the tour, a visitor comes across the Rotary element which occupies almost the entire wall.

On the other side of the room, there is a Pentomat object with a corresponding poster about it. The *point of interest* is allocated to the Pentomat object with instructions for the user to approach it. The object initially appears covered/locked but when the user approaches it, the Pentomat textures are unlocked. The *interactable* component is used for this feature and it is activated by proximity. Figure 3 shows this feature provided by the mentioned Spatial components. When the avatar moves away, the object is covered again.

(**a**) (**b**)

Figure 3. The use of Spatial components: (**a**) *point of interest* component showing information to interest the user about the object; (**b**) *interactable* component activated by the proximity of the avatar and revealing textures of the Pentomat object.

On the inner wall across the Pentomat, there is a museum section with 3D models of different types of telephones imported from Sketchfab after being scanned with the 3D Scan application. Some of the telephone models are displayed on the pedestal while others are shown as a picture on the wall. Above them, there is a respective poster on the evolution of telephony. Figure 4 shows exhibited models of telephones and a respective poster. Following the direction of movement through the museum, the visitor encounters another video that shows how the Sesa Telephone works and how the voice sounds through that telephone (it has been modelled to be as accurate as possible).

Most of the posters in the virtual museum were added in Spatial as a .pdf file format after "reserving" its space in Unity with an *empty frame* component. The .pdf format does not allow any modifications or additional features, while, for example, images can be viewed in full screen. This feature, i.e., the "zoom", is used on certain images of telephones and texts imported as images (descriptions related to cellular telephony in different languages). By clicking on the image and the plus sign appearing in the right corner of the mobile device screen, the user can show certain images or text in full screen.

Figure 4. Poster with a timeline representing the evolution of telephones with pictures and 3D models of various types of telephones below the poster.

3.1.3. Differences Between Platforms

Since we are evaluating the accessibility of a virtual museum prototype on two different platforms, we need to consider differences in navigation and interaction between platforms. Besides the obvious difference, which is the way of interacting (mobile device touchscreen and with VR controllers), there are differences caused by the limitations of the technology used, i.e., Spatial. Table 2 shows the items and functions in which platforms differ by categories named *interactable content* and *navigation*.

Table 2. Differences when visiting a virtual museum on a mobile device and in virtual reality.

Category	Metaverse Museum	Mobile Device	VR
Interactable content	Instructions	Shown first time	Non-existing
	Video	Playable after download	Non-playable
	Text as images	Zoom option	Non-interactable
	Images	Zoom option	Non-interactable
	Buttons	Tap to select	Aim the controller and press the select button
	Chair	Tap to sit	Non-interactable
Navigation	Move	Left joystick	Left controller joystick
	Jump	Right circle	'A' button on the right controller
Point of view	Change camera view or avatar's perspective	Touch and drag/pinch to zoom	Right controller joystick

The *interactable content* category is related to content that appears in the environment and with which a user can interact (depending on the platform). Firstly, when entering the virtual museum in Spatial on a mobile device, a user is exposed to instructions on how to move and interact in the environment (if a user enters Spatial space for the first time). However, in virtual reality, the user does not get any instructions. Regarding the videos in the museum, they are only playable on a mobile device, whereas in VR, a video appears just as an image on a wall without the possibility of playing it (if a user is not granted editing permissions). On a mobile device, a video must first be downloaded by clicking on the video cover image and then on a plus sign appearing in the right corner of the screen. Afterwards, it can be played by an external player on the device. Text content in the museum is available in several forms. There is text on the wall in the first museum room, text on the posters exhibited in the second museum room, and text on the informative labels of the objects. As mentioned earlier, some texts are imported in Spatial as images and they can be shown in full screen on the mobile device after clicking on them, while in VR it is not possible to zoom the images, i.e., to interact with images in that way. Interactable buttons related to changing the image of the telephone operators next to the switching central are shown on both platforms when the user is in their immediate vicinity. On a mobile device, the user selects the year (interactable button) by tapping on it with their finger, while in VR the user aims with the controller and presses the select button on the controller. Besides content relevant to the museum artefacts, there is a chair item (imported from Spatial's collection) on which a user can sit if using a mobile device, while in VR it is not interactable.

The *navigation* category is related to moving functions of the avatar, i.e., to controls used on certain platforms to move the position of an avatar. The *point of view* category includes ways of changing the camera's view and changing from first-person to third-person perspective. All pointed differences are important for evaluating the accessibility and user experience when visiting a virtual museum in the metaverse, and that is why they are considered in the questionnaire (described in the next section).

3.2. Evaluation of the Virtual Museum Prototype

The virtual museum prototype evaluation process included creating the questionnaire used for the subjective evaluation of the prototype, specifying the protocol for the experiment, and, finally, recruiting the participants.

3.2.1. Questionnaire

First, the question design process included studying literature related to key elements regarding usability, accessibility and user experience evaluation of the virtual museum [18,22,29,40,58]. The main goal of the virtual museum prototype evaluation was to gather feedback on the accessibility of the prototype from various types of users, from young users to the elderly, as well as to compare the accessibility of interacting and navigating in the virtual museum on two different platforms, i.e., the mobile device and the VR headset. Corresponding to the goal, questions are thoroughly prepared so that answers from different perspectives of various participants are useful for further prototype improvement.

The questionnaire is divided into several sections. The first part of the questionnaire relates to demographic questions and previous experience with technology. The second part of the questionnaire relates to the usability and accessibility of the virtual museum experience in the metaverse. Questions related to accessibility are based on the principles of the WCAG guidelines [29] that define how to make web content more accessible to a wider range of people with disabilities on any kind of device. Then, questions specific to experience on both platforms, mobile device and virtual reality, are following. The last part of the questionnaire is related to the social aspect and user experience of a museum visit in the metaverse in general (not specific to the device used). Although in this paper we focus on investigating barriers to accessibility and how to improve user experience, in the questionnaire we tackled the social aspect to see if users like the possibility of interacting with other users in the virtual museum.

After defining questions, the questionnaire is created in the Microsoft Forms tool and evaluated by the research team. After the improvements were made to the questionnaire, it was translated into Spanish since most of the participants were expected to be from Spain. Most of the questions in the questionnaire are choice-type questions where respondents choose an answer (or multiple answers) from a list of answers. There are also text-type questions where respondents leave a free-form answer as well as a rating and Likert-type questions that show a rating scale for the answers, so a respondent can select a value from the scale to answer each question. A total of 61 questions are prepared for the questionnaire. However, depending on respondents' answers, certain branching is applied, so not all respondents answered the same questions. For example, if some respondents answered that they used a certain option (e.g., change of the view perspective), they were then asked an additional question (e.g., how easy or difficult was it to use the pinch to zoom gesture to change the view perspective). Otherwise, they would continue with the next question.

The complete questionnaire with questions divided into sections and possible options for answering is available in Appendix A.

3.2.2. Experiment Procedure Specification

The experiment was conducted on the premises of the Universitat Politècnica de València (UPV), Spain. Before participating in the experiment, each participant signed an informed consent form (or, in the case of minors, the parents, guardian, or legal representative then signed the form).

In the experiment, every participant accessed the virtual museum prototype on two different platforms, i.e., on a mobile device and with a Meta Quest 3 virtual reality headset. The participants used their mobile devices to access the virtual museum on the Spatial platform through the link the research team provided.

To access the virtual museum on a mobile device, one needed to have a Spatial application installed on a device. If a participant did not have a mobile device or prerequisites to install the Spatial application, a research team provided one.

The research team prepared access to a metaverse museum space with a virtual reality headset (i.e., entered the Meta Quest application and navigated to Spatial and a space related to the metaverse museum). This ensured that a participant, after putting on the headset, immediately found themselves in the first room of the metaverse technological heritage museum. Before entering the virtual museum in VR, the participants were instructed on how to use the controllers because there were no instructions from the VR system upon entering the museum.

The research team made sure that the visit to the virtual museum was based on a counterbalanced design so that half of the participants first visited the virtual museum on a mobile device, while the other half first visited the virtual museum with a virtual reality headset. After the participant completed the visit on one platform, they moved to the other platform. The only limitation during the experiment was the number of users in the metaverse museum at the same time, which was 8 (e.g., 4 participants accessing the museum on a mobile device and 4 participants in VR).

The visit to the virtual museum with each of the two devices lasted approximately 10–15 min, during which a participant visited both rooms of the museum and interacted with different types of objects. After a participant visited the virtual museum on both platforms, a previously described questionnaire was used to gather data about the accessibility and user experience in the metaverse museum. The questionnaire was answered anonymously, and it was filled out right after the metaverse museum experience. On average, it took participants about 15 min to complete the questionnaire.

3.2.3. Participants Recruitment

Since the goal of the virtual museum prototype evaluation is to collect feedback from different types of users, we included participants of different ages, with special emphasis on young users as the usual target group for university museums such as the Telecommunication Museum Vicente Miralles Segarra. We also included participants from young adults to the elderly because of their different needs related to technology, so that we can have two groups (younger vs. older users) with comparing number of respondents. The objective is to analyse whether there is a difference in perception of accessibility and user experience between young participants and adults in relation to different elements of the metaverse museum (e.g., readability, ease of navigation, certain platform-dependent functionalities and overall satisfaction) between different ages. Participants younger than 18 years old form the *Young* subgroup, while participants 18 years old and older form the *Adult* subgroup.

The selection criteria to participate in the study were to be 15 years old or older, to guarantee that the participants were mature enough for the experience and participation in the study, especially as responding to a long questionnaire could be challenging for younger children. To recruit young participants (mostly teenagers), we included students from secondary education institutes. Specifically, a teacher from the Valencian high school IES Cabanyal was contacted and visits on two different days to UPV ETSIT were arranged. The teacher provided students with the information about the study and the informed consent form so that those who wanted to participate could have the authorization of their parents, guardians or legal representatives to participate. Besides them, UPV students involved in courses of the professors participating in the research were also asked to participate in the study. Participants who are 55 years old or older are mostly recruited from the Senior University, which is part of the Vice-Rectorate for Art, Science, Technology and Society of the UPV. To recruit participants for the age groups in between, the study was disseminated among UPV staff and their contacts. A total of 64 voluntary subjects participated in the experiment. Photos of the participants during the experiment are shown in Figure 5a,b.

(**a**) (**b**)

Figure 5. Participants on mobile devices and in VR during the experiment: (**a**) students from the Valencian high school IES Cabanyal; (**b**) participants from the Senior University.

3.2.4. Data Collection and Statistical Analysis

Data were collected using the Microsoft Forms tool, as described in Section 3.2.1. Participants completed a structured questionnaire, and responses were automatically recorded by the platform. Upon completion of the data collection, the responses were exported from Microsoft Forms as a Microsoft Excel Worksheet (Excel version 2503) for further processing and analysis.

The data analysis in this study was performed using both Excel and IBM SPSS Statistics. The dataset was initially reviewed and cleaned in Excel. Excel was also used to compute descriptive statistics, including frequency distributions and measures of central tendency, and to generate visual representations of the data. Subsequently, the data were imported into IBM SPSS Statistics, version 30.0.0.0, for inferential statistical analysis. All statistical tests were conducted using a 0.05 significance level.

We employed a combination of descriptive and inferential statistical methods to analyse the data. Descriptive statistics were used to summarize and describe participants' responses and to provide an overview of general trends observed in the accessibility evaluation of the metaverse museum. Afterwards, we conducted inferential statistical tests. Given the nature of our data, which included binary/nominal variables and ordinal data from Likert-scale items, non-parametric tests were used since they do not require the assumption that the data follows a normal distribution. Due to the volume of tests conducted, we focused on reporting only statistically significant results.

Inferential statistical tests were applied as follows. The chi-square test was applied to determine whether there is a significant association between the *Young*/*Adult* age groups and different binary/nominal variables that were collected in the questionnaire. In cases when more than 20% of cells in the contingency table had frequencies less than 5, Fisher's exact test was applied instead of the chi-square test. The Mann–Whitney U test was applied to determine whether there is a significant difference in dependent variables represented by Likert-scale questions (ordinal variables) between the *Young* and the *Adult* age groups. For the ratings related to the overall satisfaction of the visit to the metaverse museum on the mobile device compared to the visit in VR, we report the results of a within-subject test (Wilcoxon signed-rank test).

4. Results and Feedback Analysis

This section is organized as follows. First, we present the demographic characteristics of participants, including age distribution, gender, education level, type of difficulty/disability, frequency of smartphone/tablet use, and experience with immersive technologies (Section 4.1).

To address RQ1 regarding the perception of accessibility between age groups in different aspects of the metaverse museum and on two different platforms (mobile device and VR), we first present the results common to both platforms (Section 4.2). They are related to the readability of texts (Section 4.2.1), artefact size (Section 4.2.2), ease of element selection (Section 4.2.3), understanding of the teleport portal (Section 4.2.4), and informative content (Section 4.2.5).

Afterwards, we are reporting the results concerning accessibility for a certain platform since they differ in interaction, i.e., controls and way of navigating in space, as well as they have platform-specific functions in the metaverse museum. Section 4.3 presents mobile-specific accessibility results, covering mobile controls (Section 4.3.1), navigation and avatar speed (Section 4.3.2), zoom functions (Section 4.3.3), and video playback (Section 4.3.4). Section 4.4 focuses on VR-specific accessibility aspects, including VR controls (Section 4.4.1), navigation and avatar speed (Section 4.4.2), camera's point of view (Section 4.4.3), and VR-related discomfort (Section 4.4.4).

In Section 4.5, we present results related to the usability of the metaverse museum, first comparing general usability between mobile and VR (Section 4.5.1), and then examining age group differences (Section 4.5.2).

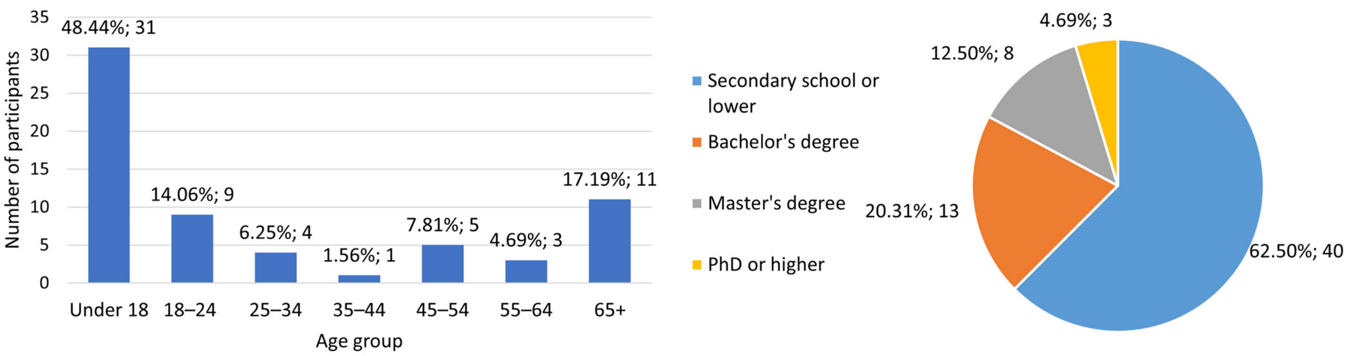
Section 4.6 focuses on overall user experience and the social aspect of the metaverse museum, including satisfaction with the interior design of the museum, artefact quality, and interactivity of the artefacts (Section 4.6.1), then overall enjoyment in the metaverse museum, interest in repeat visits, and willingness to recommend (Section 4.6.2), and preferences for social interaction in the metaverse (Section 4.6.3).

Sections 4.5 and 4.6 provide the basis for answering RQ2 regarding user satisfaction across platforms, as well as provide insight into what can be improved in the metaverse museum for better user experience. RQ3, which is related to design recommendations to improve the accessibility and inclusivity of metaverse museums, is addressed in the discussion section (Section 5), where findings are synthesized and interpreted.

To enhance the interpretability of the results, various types of visual representations are employed throughout the Results section. Clustered bar charts and pie charts are used to present the distribution of Yes/No responses across different questionnaire items. Stacked bar charts are utilized where age-specific distributions are of interest, allowing for clearer comparison between the Young and Adult participant groups. Bar charts are also used to illustrate the distribution of responses to multiple-choice questions, such as suggestions for improving accessibility of navigation or text readability. Finally, clustered column charts are used to display participant ratings on a five-point Likert scale for different aspects of accessibility, usability, and user experience.

4.1. Participants Demographic Analysis

Of the total number of participants in the experiment (63), 43 identified as *male*, 20 as *female*, and one as *other*. The distribution of participants per age group is shown on a graph in Figure 6a while Figure 6b presents the distribution of participants by education level. The experiment involved 31 participants under the age of 18 (*Young* age group), and 33 participants aged 18 and over (*Adult* age group). Most of the participants (62.50%) have completed secondary school or lower education level, 20.31% of the participants have completed a bachelor's degree, 12.50% of the participants have completed a master's degree and 4.69% have a PhD or higher degree of education.



(**a**) (**b**)

Figure 6. Distribution of participants by (**a**) age group—absolute frequency and (**b**) education level—relative frequency (N = 64).

Around 22% of participants (14 of them) indicated that they have some form of disability/difficulty. To be more precise, 10 participants indicated that they have visual impairments such as myopia, astigmatism, colour blindness, near/farsightedness and reduced vision, two participants indicated that they have specific learning difficulties such as ADHD, one participant indicated they have motor disability (paraplegia), and one participant indicated having a hearing and visual impairment.

Almost all participants stated that they use a smartphone or tablet every day (only 6.25% of participants stated that they use it several times a week). Regarding previous experience with immersive technologies, 23.44% (15) of participants stated that they had none, while 77.56% (49) of participants had previous experience with immersive technologies. The technology that participants had the most experience with was virtual reality (87.76% of participants with prior experience), followed by handheld augmented reality (61.22%), 360° video (57.14%), 360° audio (42.86%), and the fewest (10.2%) tried head-worn augmented/mixed reality and haptic content. Figure 7 shows the distribution of immersive technologies according to the number of participants who already had experience with them (N = 49). Most participants had experience with more than one technology.

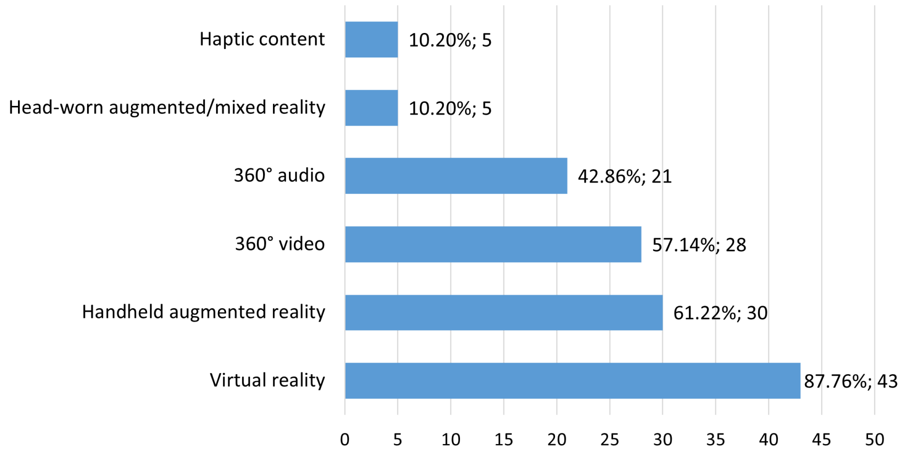


Figure 7. Distribution of immersive technologies by the frequency of participants who experienced them ($N_{experience}$ = 49, multiple answers possible).

4.2. Platform-Independent Results

4.2.1. Text

The first item that was evaluated in the metaverse museum in the context of accessibility is the text. Participants were asked to answer *Yes* or *No* to questions about whether the text displayed in the museum is easy to read, regardless of the platform. We investigated three different forms of text: text on parts of the environment such as walls, text on the information labels (points of interest or interactive buttons) and text on the posters. The distribution of responses for each form of text is shown in a bar chart in Figure 8. The results show that the text on the posters was rated with the highest number of *No* answers compared to the other two text formats. No significant associations were found between the *Young*/*Adult* age groups and the binary variables in these questions.

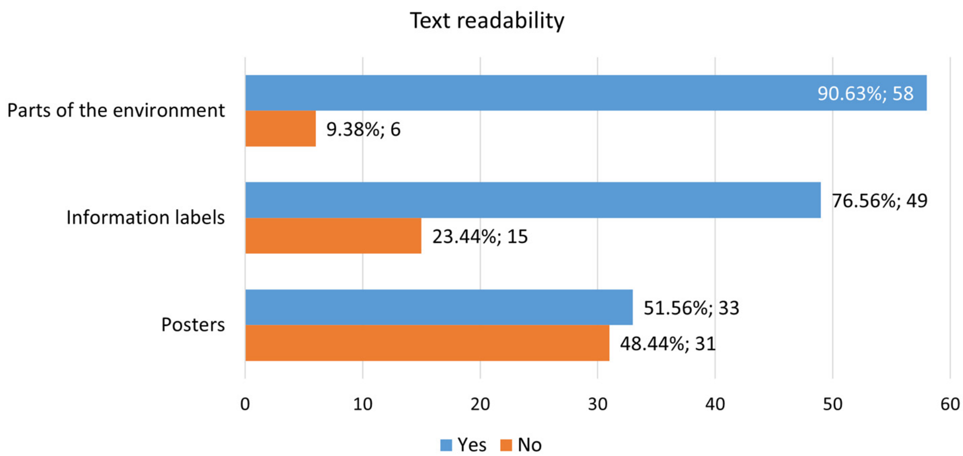


Figure 8. Clustered bar chart showing the distribution of Yes/No answers according to the number of participants for items related to text readability in the metaverse museum (N = 64).

Participants were then asked to select from the given options and/or add their options to answer what would make it easier to read the text on the museum artefacts. Figure 9 shows the distribution of the options chosen by the participants, categorised by the *Young* and *Adult* age groups. The *Zoom option* was chosen by most participants (59.38%), followed by *Changing the font size* option (39.06%), the *Read aloud option* (29.69%) and the *Making the text simpler or more understandable* option (20.31%). Other options were selected by less than 8% of participants. The *Adult* age group stands out for the *Zoom option* and the *Read aloud option*, as more adults suggested these options than the young participants, while for the other options the distribution of responses by age group is more or less equal.

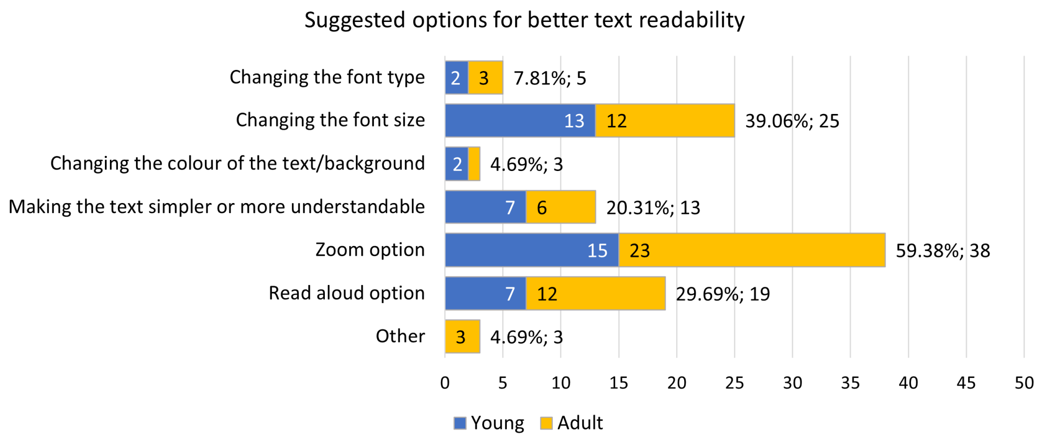


Figure 9. Stacked bar chart showing the distribution of chosen options for improving the readability of the museum artefact text, categorised by the number of participants from *Young* and *Adult* age groups (N = 64, multiple answers possible).

4.2.2. Museum Artefacts

The size of the museum artefacts was the next item evaluated in relation to whether they were large enough for the size of their avatar. Most participants (89.06%) responded that the artefacts were big enough, while others (10.94%) responded that they were not. The distribution of responses in relation to the size of the artefacts is shown in Figure 10.

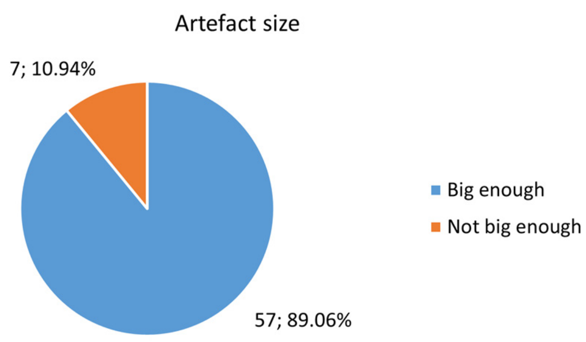


Figure 10. A pie chart showing the distribution of answers related to the size of the museum artefacts (N = 64).

Next, the participants were asked to select the options that would, in their opinion, help to observe artefacts better. A certain number of participants (23 participants, 35.94%) answered that for them it was easy to observe everything and did not suggest any option while others selected one or more options. Figure 11 shows the distribution of selected options by the participants, categorised by the *Young* and *Adult* age groups. The *Zoom option for all artefacts* was suggested by 33 participants (51.56% of 64 participants), with more adults suggesting this option than young participants. Some of the participants suggested larger artefacts by default (14.06%) and some of them (9.38%) suggested adjustable size for the artefacts.

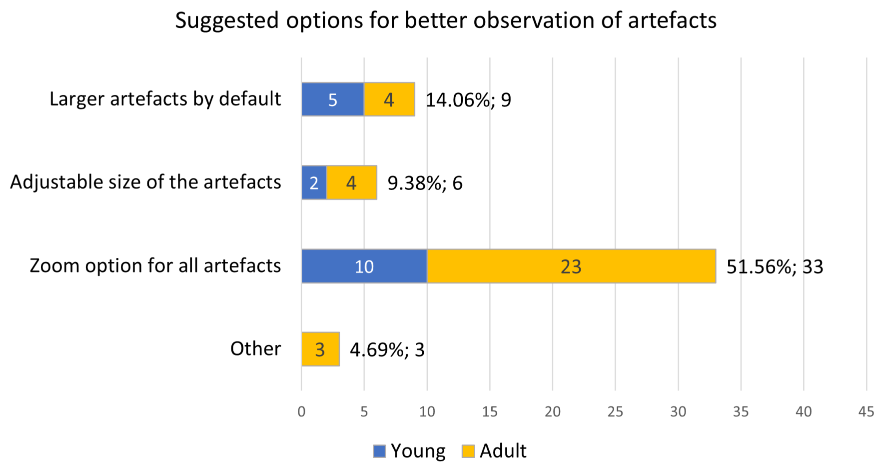


Figure 11. Stacked bar chart showing the distribution of suggested options for better observation of the artefacts, categorised by the number of participants from *Young* and *Adult* age groups (N = 64, multiple answers possible). Participants who did not suggest any option were excluded.

4.2.3. Interactive Elements

Ease of selection of different telephony operators, one of the interactable components of the museum, was evaluated by asking participants to choose a rating from 1 to 5 where: 1 = Very difficult; 2 = Difficult; 3 = Neither difficult nor easy; 4 = Easy; 5 = Very easy. The distribution of ratings by number of participants is shown in Figure 12. Measures for descriptive statistics are as follows: mean M = 2.95, median C = 3, standard deviation SD = 1.09, 95% confidence interval for the mean CI = 0.27.

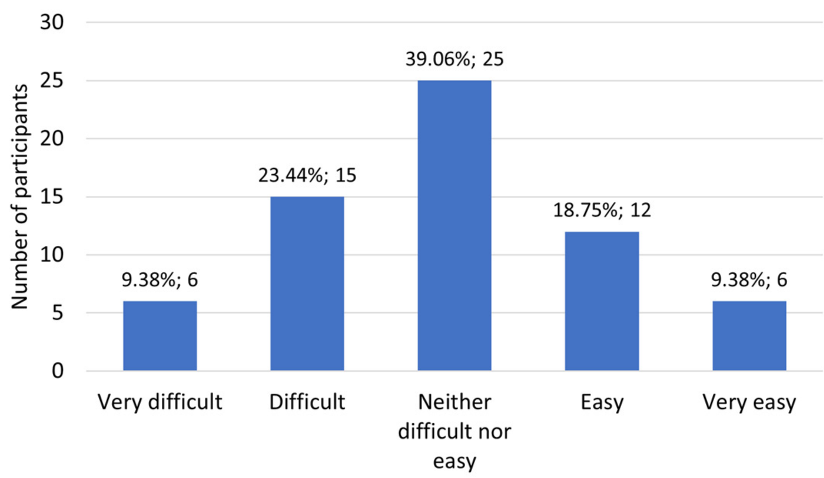


Figure 12. Distribution of participants' ratings for the ease of selection of different telephony operators (N = 64).

Afterwards, the participants were asked what would make the selection of different telephony operators easier as well as to select the reasons why they found this interaction difficult. The distributions of answers are shown in the bar charts in Figure 13a,b. An option that was suggested the most (by 45.31% of participants) includes additional instructions on how to select. The "Interactable years shown at once" option was suggested by 21.88% of participants, while a different interaction type for selection was suggested by 15.63% of participants. Most of the participants found it difficult to select different telephone operators because they did not know how to change to another telephone operator (37.50%), or they did not see the option to select (35.94%). The reason for 23.44% of participants was that the display of years kept changing depending on their position.

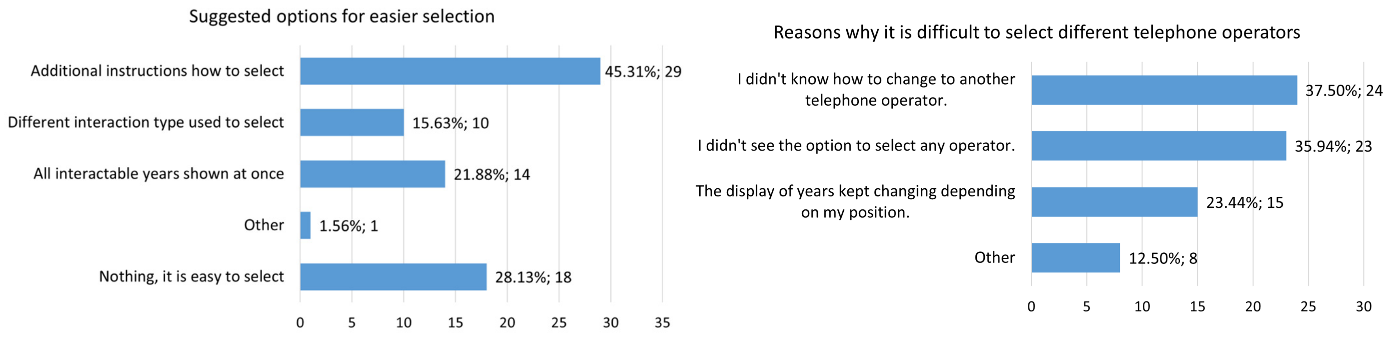


Figure 13. Bar charts showing the distribution of answers related to the selection of telephony operators: (**a**) suggested options for easier selection (participants who did not suggest any option are also shown in the graph), (**b**) reasons why it was difficult to select different telephone operators. Multiple answers were possible (N = 64).

4.2.4. Teleport Portal

Participants were asked whether they had intentionally teleported from one room of the metaverse museum to another on both platforms. Most participants (73.44%) teleported through the portal intentionally, while the rest (26.56%) did not do so on at least one platform. Figure 14 shows the distribution of answers by the participants, categorised by the *Young* and *Adult* age groups. A chi-square test of independence was performed to examine the relation between age groups (*Young* and *Adult*) and intentional teleportation. The relation between these variables was significant: χ^2 (1, N = 64) = 12.465, $p < 0.001$. A Phi coefficient is used to determine the effect size, i.e., how strong the association between the variables is: r = 0.441. The young participants were more likely to teleport intentionally than the adults.

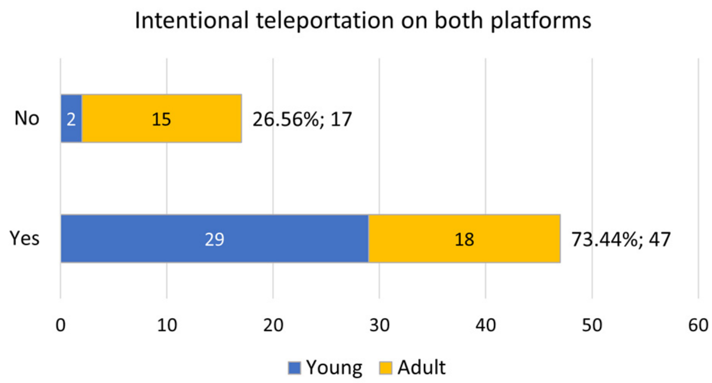


Figure 14. A stacked bar chart showing the distribution of Yes/No answers, categorised by the number of participants from *Young* and *Adult* age groups (N = 64).

Afterwards, the participants were asked to select from the options provided and/or to add their options to answer what would facilitate teleporting with intent. Figure 15 shows the distribution of selected options by the participants. An option that was suggested the most (by 43.75% of participants) includes a confirmation of whether they want to teleport. The instructions on how to teleport were suggested by 26.56% of participants, while 17.19% of participants suggested that information on why to teleport would be beneficial. Some of the participants (14.06%) suggested that it would be beneficial if there were the option to come back to the initial room.

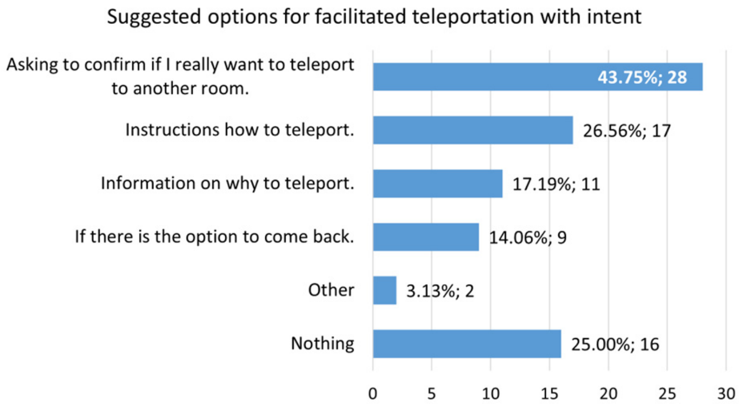


Figure 15. A bar chart showing the distribution of suggested options to facilitate teleportation with intent (N = 64, multiple answers possible). Participants who did not suggest any option or for whom teleportation was easy were excluded.

4.2.5. Helpful and Informative Elements

Next, the participants were asked whether elements such as arrows on the floor and information labels on the artefacts were helpful and informative for them. The distribution of answers for each element can be seen on a clustered bar chart in Figure 16. The results show that arrows on the floor were considered helpful for 73.44% of participants while information labels were considered helpful and informative for 92.19% of participants.

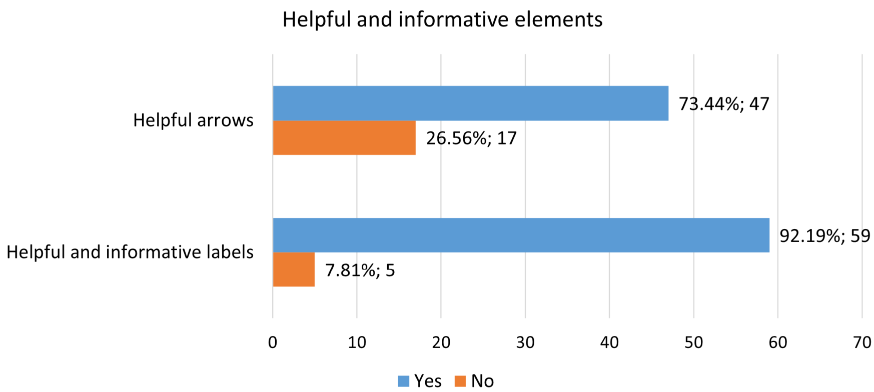


Figure 16. Clustered bar chart showing the distribution of Yes/No answers according to the number of participants for items related to helpful and informative elements in the metaverse museum (N = 64).

Afterwards, the participants were asked to select from the options provided and/or to add their options to answer what would make reading the information labels more helpful and informative. Figure 17 shows the distribution of selected options by the participants. An option that was suggested the most (by 50% of participants) includes showing more information about an artefact by selecting the label. The next option suggested by 32.81% of participants includes showing more information about possible interaction with an artefact by selecting the label. Some of the participants (7.81%) suggested that it would be beneficial if the information label did not cover parts of an artefact and that it is placed elsewhere.

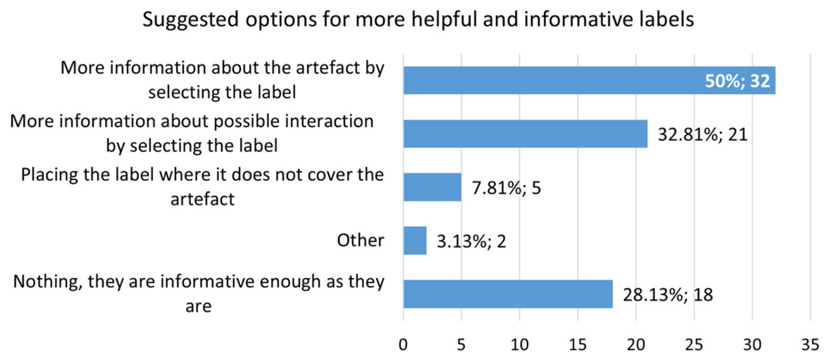


Figure 17. A bar chart showing the distribution of suggested options to make labels more helpful and beneficial (N = 64, multiple answers possible). Participants for whom information labels were helpful enough are also shown on the graph.

4.3. Mobile Device Results

In the experiment, participants used different types of smartphone devices, as shown in Figure 18. Most of them (39.06% of participants) used a Samsung device, then a Xiaomi device was used by 23.44% of participants, while an Apple device (an iPhone) was used by 21.88% of participants. Devices from each category were different models of the same brand. The others (15.62% of participants) used smartphone devices from other brands, such as Oppo, Huawei, Honor, Sony, Google and Vivo.

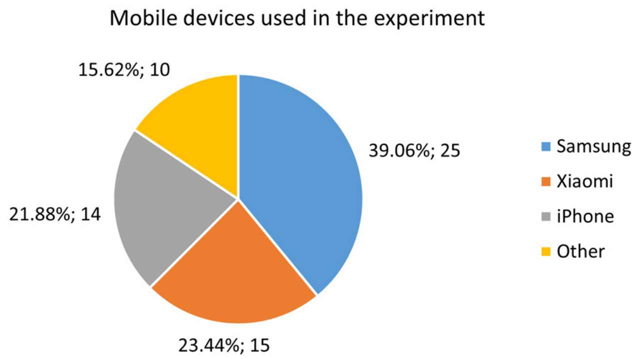


Figure 18. Distribution of types of mobile devices used in the experiment by the participants (N = 64).

4.3.1. Mobile Controls

Participants who used the Spatial application for the first time during the experiment were given instructions on how to use the controls after entering the metaverse museum. Therefore, they were asked if the instructions on how to use the controls on the mobile device (i.e., joystick to move, circle to jump, change the view of the camera) were clear and understandable. We then investigated whether the participants found that interaction controls were big enough and if they were placed in the right place on the screen. The instructions, as well as the appearance and placement of the interaction controls, are provided by the Spatial platform. The distribution of answers for each question related to interaction controls can be seen on a clustered bar chart in Figure 19. The results show that most participants (79.69%) found the instructions clear and understandable, as most participants found that interaction controls were big enough (92.19% of participants) and in the right place on the screen (96.88% of participants).

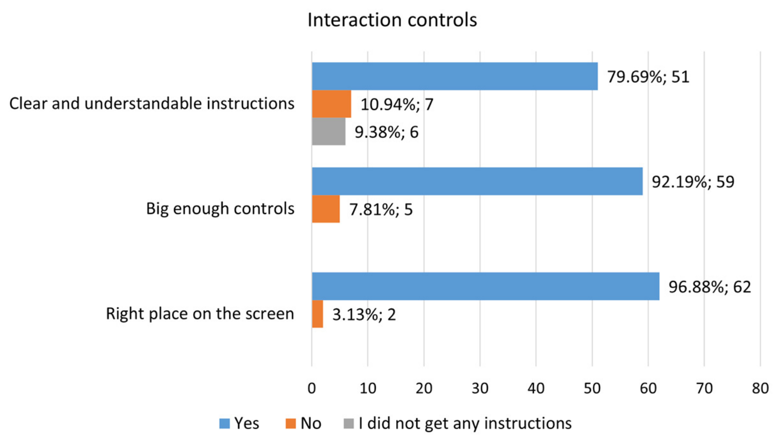


Figure 19. A clustered bar chart showing the distribution of answers according to the number of participants for questions related to controls' instructions, size and placement on the mobile device (N = 64).

4.3.2. Mobile Navigation

On the question related to ease of navigation through the museum on a mobile device, participants answered by choosing a rating from 1 to 5 where: 1 = Very difficult; 2 = Difficult; 3 = Neither difficult nor easy; 4 = Easy; 5 = Very easy. The distribution of ratings by number of participants is shown in Figure 20. Measures for descriptive statistics are as follows: mean M = 3.81, median C = 4, standard deviation SD = 1.23, 95% confidence interval for the mean CI = 0.3. A Mann–Whitney U test was performed to compare ratings for the ease of navigation on a mobile device between the age groups *Young* and *Adult*. The results showed that the ratings of the young participants were significantly higher than the adult group ($Z = -4.473$, $p < 0.001$).

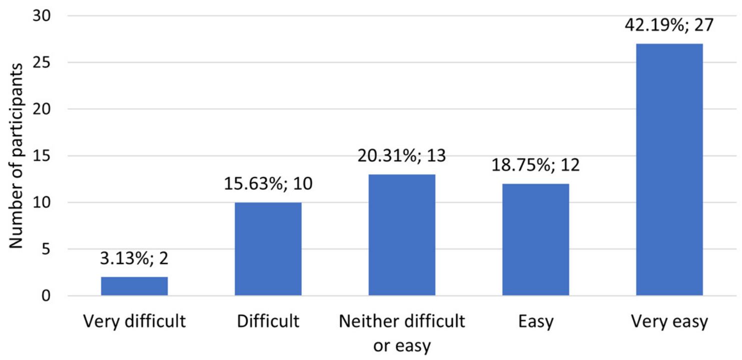


Figure 20. Distribution of participants' ratings for the ease of navigation through the museum on a mobile device (N = 64).

The avatar speed was the next item evaluated concerning navigation in the museum on the mobile device. Most of the participants (70.31%) answered that the avatar's speed was appropriate, while 29.69% of participants answered that it was not, i.e., it was too fast. The distribution of the answers related to the avatar's speed is shown in Figure 21. A chi-square test of independence was performed to examine if there is a significant association between age groups (*Young* and *Adult*) and their experience related to the avatar speed on a mobile device. The relation between these variables was significant: χ^2 (1, N = 64) = 11.532, $p < 0.001$, r = 0.424. The young participants were more likely to perceive the avatar's speed on the mobile device as appropriate than the adults who were more likely to perceive it as too fast.

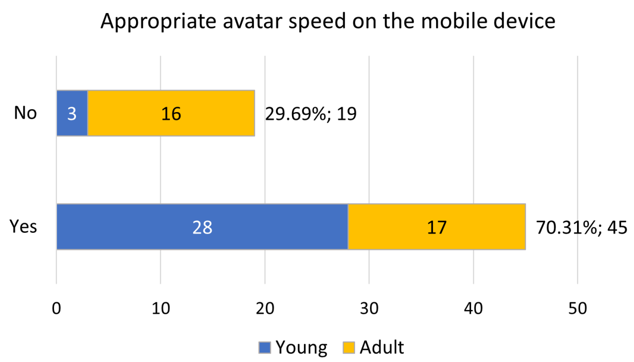


Figure 21. Clustered bar chart showing the distribution of Yes/No answers for the question related to the appropriateness of the avatar speed on the mobile device, categorised by the number of participants from the *Young* and *Adult* age groups (N = 64).

Next, the participants were asked to select the options that would, in their opinion, make navigation on the mobile device more intuitive and easier. Figure 22 shows the distribution of selected options by the participants. An option that was suggested by 34.38% of participants includes an easier way to change the view perspective (easier than the current rotation of the camera using touch gestures on the screen). Slowing down the movement on the mobile device was suggested by 28.13% of participants, while 10.94% of participants suggested that it would be beneficial to have buttons instead of a joystick for navigation.

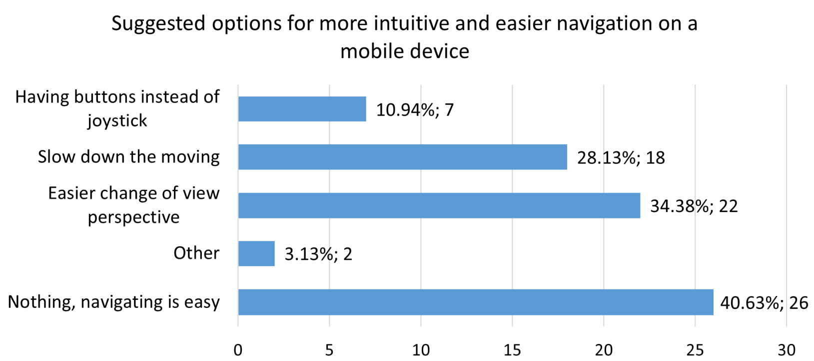


Figure 22. A bar chart showing the distribution of suggested options to make navigation on a mobile device more intuitive and easier (N = 64, multiple answers possible). Participants for whom navigation was easy are also shown on the chart.

4.3.3. Zoom Functions

Participants had two ways to get a better view of the artefacts, by using the pinch-to-zoom gesture (which also changes the viewing perspective) or by clicking on the zoom button after selecting a textual artefact. We investigated how many participants used those functions. The distribution of the answers related to the engagement with zoom functions is shown in Figure 23. The results show that most participants (68.75%) engaged with pinch-to-zoom gestures to better view the artefacts. However, only around half of the participants engaged with the zoom button (51.56%) while 21.88% did not even see the option to zoom by clicking on a button. A chi-square test of independence was performed to examine if there is a significant association between age groups (*Young* and *Adult*) and their engagement with zoom functions on a mobile device. While there was no significant association between age groups and the use of a zoom button, the test revealed that the association between the age groups and the use of pinch-to-zoom gestures was significant: χ^2 (1, N = 64) = 3.960, $p = 0.047$. A Phi coefficient is used to determine the effect size, i.e., how strong the association between the variables is: r = 0.249. Adult participants are less likely to use the pinch-to-zoom gestures on a mobile phone than the young participants.

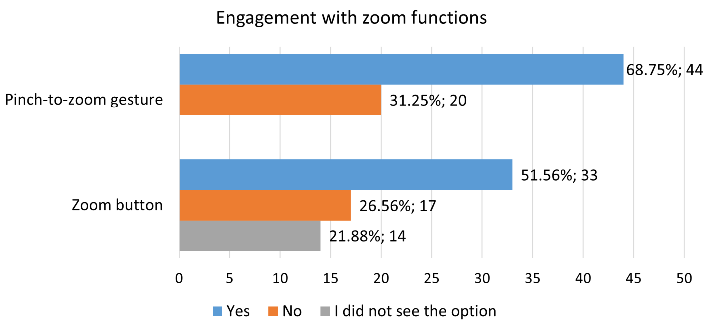


Figure 23. A clustered bar chart showing the distribution of answers according to the number of participants for questions related to engagement with the zoom functions on the mobile device (N = 64).

On the question related to the ease of pinch-to-zoom gestures on a mobile device, participants who used this zoom function ($N_{pinch\text{-}to\text{-}zoom}$ = 44) answered by choosing a rating from 1 to 5 where: 1 = Very difficult; 2 = Difficult; 3 = Neither difficult nor easy; 4 = Easy; 5 = Very easy. The distribution of ratings by number of participants is shown in Figure 24. Measures for descriptive statistics are as follows: mean M = 4.07, median C = 4, standard deviation SD = 1.02, 95% confidence interval for the mean CI = 0.3. A Mann–Whitney U test was performed to compare ratings for the ease of the pinch-to-zoom gesture on a mobile device in age groups *Young* (N_{young} = 25) and *Adult* (N_{adult} = 19). The results showed that the ratings of the young participants were significantly higher than the adult group ($Z = -2.233$, $p = 0.026$).

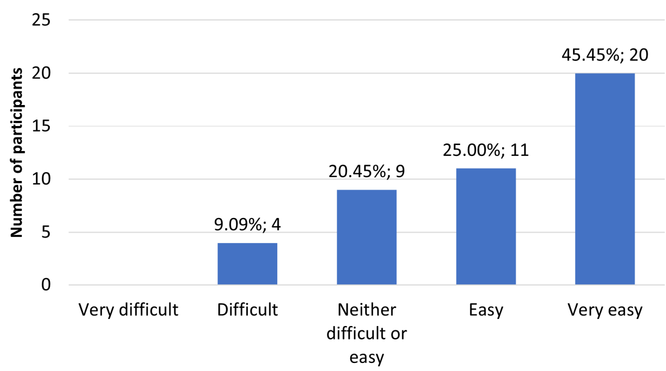


Figure 24. Distribution of participants' ratings for the ease of use of pinch-to-zoom gestures on a mobile device ($N_{pinch\text{-}to\text{-}zoom}$ = 44).

4.3.4. Videos

For the museum artefacts in the form of videos, we asked the participants if the content in the videos was easy to perceive, i.e., to see and hear. An approximate number of participants responded that the content in videos was easy to perceive (43.75%) and that they did not play the videos (46.87%), while a few participants (9.38%) responded that the content was not easy to perceive. Those participants who answered that they did not play videos were asked to select the reason(s) why they did not play them. Most of them answered that they did not know there was an option to play a video (20 participants) or how to play a video (6 participants). Those participants who answered that the videos were not easy to perceive suggested what would be beneficial to better perceive videos. All of them answered that captions (the same language as the spoken audio) would be beneficial, while some of them suggested subtitles and audio prerecorded in different languages. The results can be observed in Figure 25.

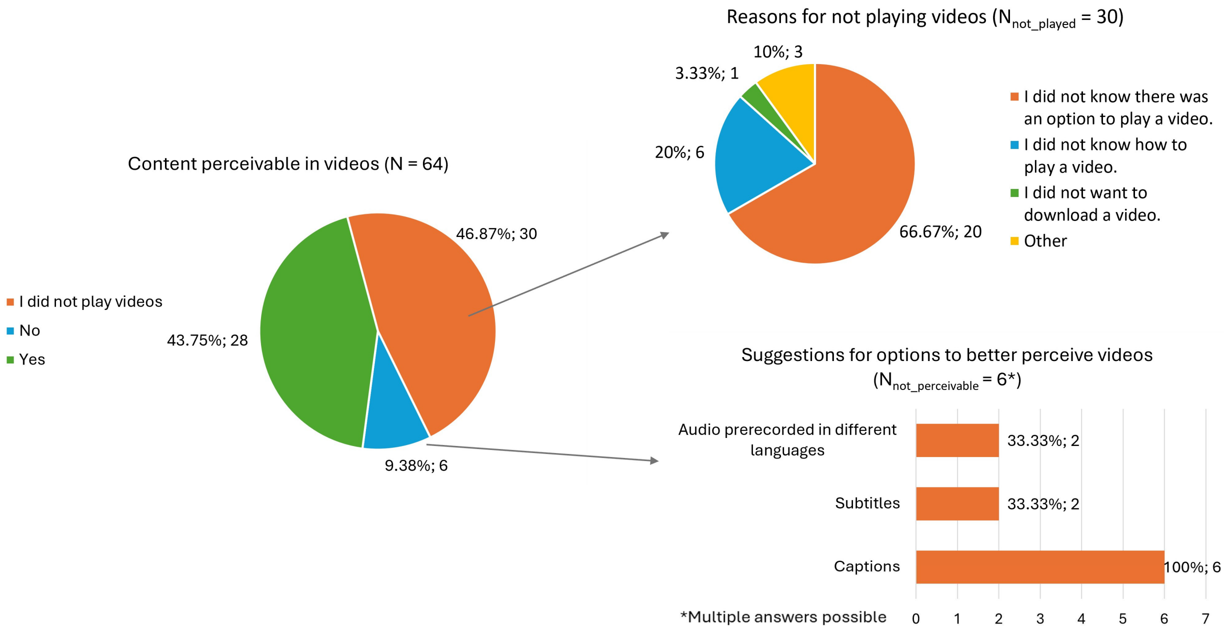


Figure 25. Charts with distributions of answers: pie chart on the left—answers related to whether the video content is perceivable (N = 64), pie chart on the top right—reasons for not playing videos (N_{not_played} = 30) and bar chart on the bottom right—suggested options to make videos more perceivable ($N_{not\_perceivable}$ = 6, multiple answers possible).

Afterwards, the participants were asked to select from the options provided and/or to add their options to answer what would make playing the videos on the mobile device easier. Figure 26 shows the distribution of selected options by the participants. An option that was suggested the most (by 42.19% of participants) includes information that there is a video. Playing videos without downloading them first was suggested by 23.44% of participants, while 20.31% of participants suggested that instructions on how to play a video would be beneficial.

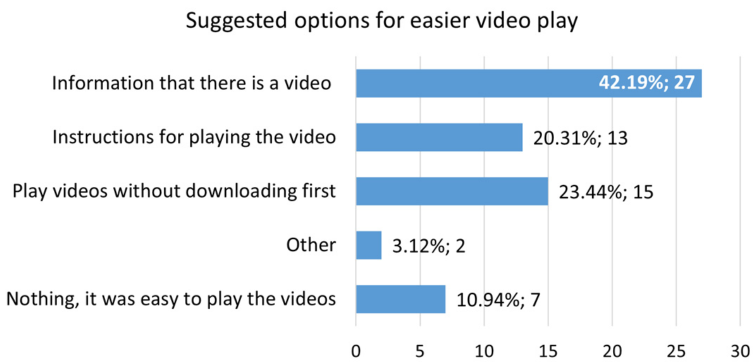


Figure 26. A bar chart showing the distribution of suggested options to make video play easier (N = 64, multiple answers possible). Participants for whom it was easy to play the videos are also shown on the graph.

4.4. Virtual Reality Results

4.4.1. VR Controls

Participants were asked if they found the VR equipment (headset and controllers) easy to understand and use. Only two participants (3.13%) responded that they found the

VR equipment difficult to understand and use, while almost all participants responded that it was easy to understand and use. Unlike on a mobile device, upon entering a metaverse museum in VR, users do not get instructions on how to use VR controls. Therefore, the participants were asked for an opinion about whether it would be helpful to have written instructions on how to use the VR controllers to navigate and interact. Most of the participants (67.19%) responded that instructions would be helpful, while 23.44% of participants do not know/do not have an opinion. Only 9.38% think that instructions would not be helpful. The distribution of answers for both questions is shown in Figure 27.

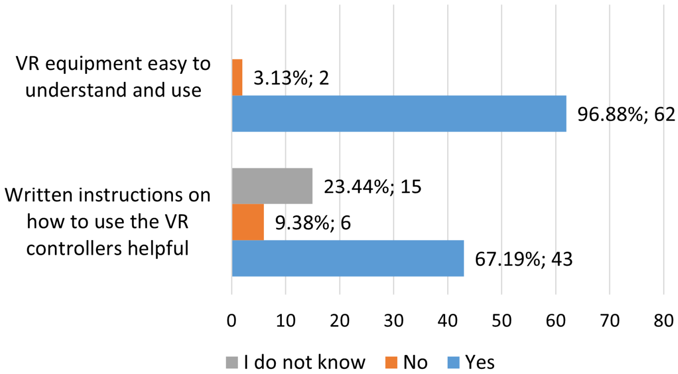


Figure 27. Clustered bar chart showing the distribution of answers according to the number of participants for items related to VR equipment and controls (N = 64).

4.4.2. VR Navigation

On the question related to ease of navigation through the museum in VR, participants answered by choosing a rating from 1 to 5 where: 1 = Very difficult; 2 = Difficult; 3 = Neither difficult nor easy; 4 = Easy; 5 = Very easy. The distribution of ratings by number of participants is shown in Figure 28. Measures for descriptive statistics are as follows: mean M = 3.83, median C = 4, standard deviation SD = 0.92, 95% confidence interval for the mean CI = 0.22. A Mann–Whitney U test was performed to compare ratings for the ease of navigation in VR in the age groups *Young* and *Adult*. The results showed that the ratings of the young participants were significantly higher than the adult group ($Z = -2.408$, $p = 0.016$).

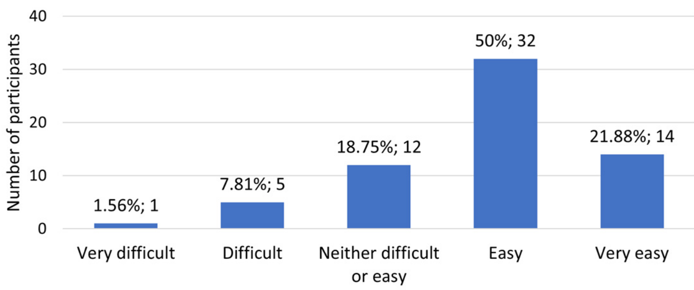


Figure 28. Distribution of participants' ratings for the ease of navigation through the museum on in VR (N = 64).

The avatar speed in VR was evaluated next. Most of the participants (75%) answered that the avatar's speed was appropriate, while 25% of participants answered that it was not, i.e., it was too fast (20.31%) or too slow (4.69%). The distribution of the answers related to the avatar's speed in VR is shown in Figure 29. A chi-square test of independence was performed to examine if there is a significant association between age groups (*Young* and *Adult*) and their experience related to the avatar speed on a mobile device. The relation between these variables was significant: χ^2 (1, N = 64) = 7.528, p = 0.006. A Phi coefficient was used to determine the effect size, i.e., how strong the association between the variables is: r = 0.343. The young participants were more likely to perceive the avatar's speed in VR as appropriate than the adults, who were more likely to perceive it as too fast.

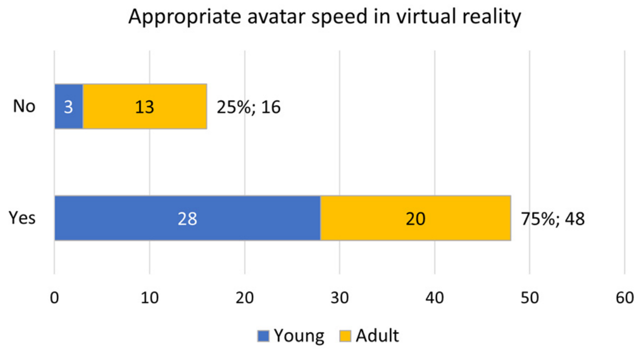


Figure 29. Stacked bar chart showing the distribution of Yes/No answers for the question related to the appropriateness of the avatar speed in VR, categorised by the number of participants from *Young* and *Adult* age groups (N = 64).

Next, the participants were asked to select the options that would, in their opinion, make navigation in VR more intuitive and easier. Figure 30 shows the distribution of selected options by the participants. An option that was suggested by 40.63% of participants includes the Help option, which can be opened at any time, while the option including instructions on how to navigate and use controllers upon entering a metaverse museum was suggested by 35.94% of participants. The possibility of different ways of movement (e.g., teleportation) was suggested by 10.94% of participants.

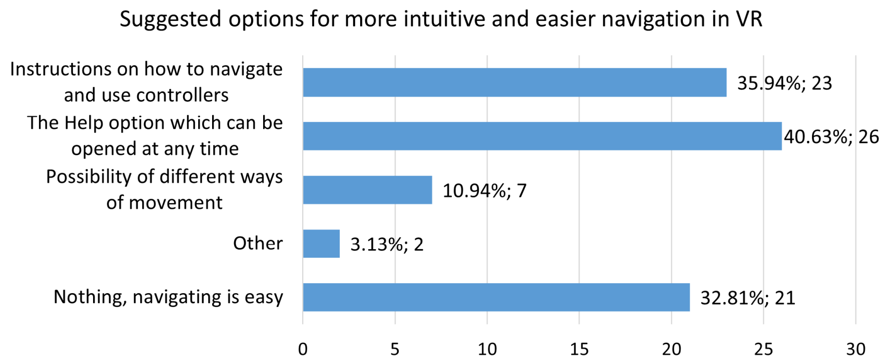


Figure 30. A bar chart showing the distribution of suggested options to make navigation in VR more intuitive and easier (N = 64, multiple answers possible). Participants for whom navigation was easy are also shown on the chart.

4.4.3. Point of View

We investigated how many participants used the joystick on the right controller to change to a different point of view of the camera and what point of view was the most comfortable for them. The distribution of the answers for both questions is shown in Figure 30. The results shown in Figure 31a show that 50 participants (78.13%) used the joystick to change the point of view. Figure 31b shows that, for most of the participants who changed the point of view with a joystick (40 participants, i.e., 80%), the most comfortable point of view was the point of view from the eyes of the avatar, while for the others (20%) the most comfortable view was the view from behind the avatar.

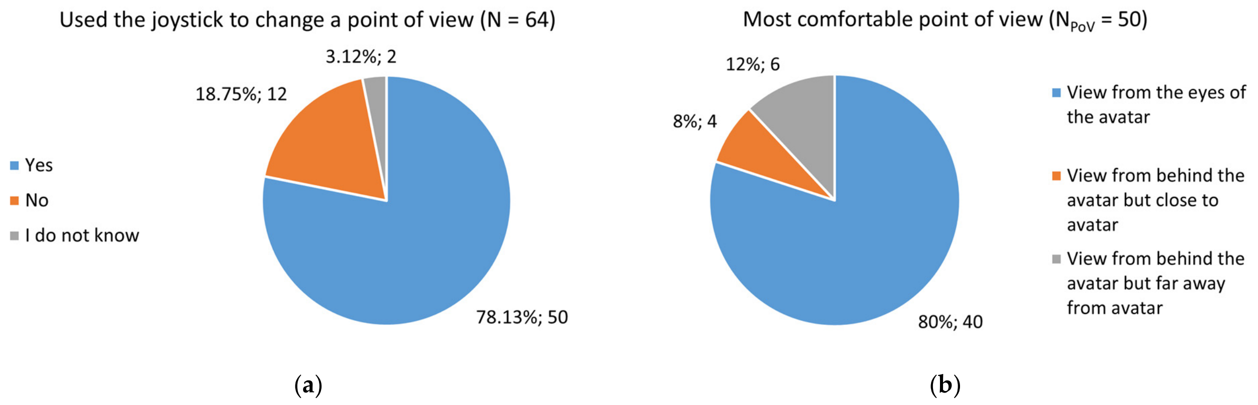


Figure 31. Pie charts with distributions of answers by participants related to the camera's point of view: (**a**) engagement with a joystick that changes a point of view (N = 64), (**b**) most comfortable point of view (N_{PoV} = 50).

4.4.4. VR Discomfort

We investigated whether participants felt discomfort or motion sickness while visiting the metaverse museum with the Meta Quest 3 device. The results show that 32.81% of participants did feel some of the VR-induced effects. Therefore, they were asked to describe their discomfort, and most answered that they felt dizziness, then nausea, headache, and eye fatigue, during or after taking the headset off. The results can be observed in Figure 32.

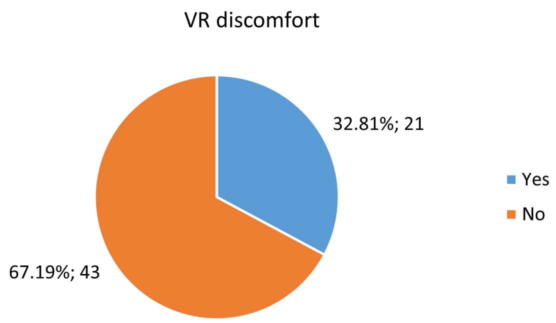


Figure 32. The distribution of answers for feeling discomfort during or after the VR experience (N = 64).

4.5. Comparison of Mobile Device and Virtual Reality Usability

4.5.1. Differences in General

Participants were asked the same four usability questions related to the usability of the metaverse museum for both platforms, the mobile device and the VR headset. They were asked to respond to four statements by choosing a rating from 1 to 5 where: 1 = Strongly disagree; 2 = Disagree; 3 = Neither disagree nor agree; 4 = Agree; 5 = Strongly agree. Distributions of ratings for both platforms are shown in Figure 33a–d. Descriptive statistics can be observed in Table 3.

We investigated whether there was a significant difference between the ratings depending on the platform (mobile device or VR) by looking at the participants in total. The Wilcoxon signed-rank test was performed (N = 64) and it showed a significant difference in the subjective ratings for the overall satisfaction with the metaverse museum on a mobile device compared to the overall satisfaction with the metaverse museum in VR ($Z = -2.314$; $p = 0.021$; $r = 0.289$). The ratings for the VR platform were significantly higher than for the mobile device.

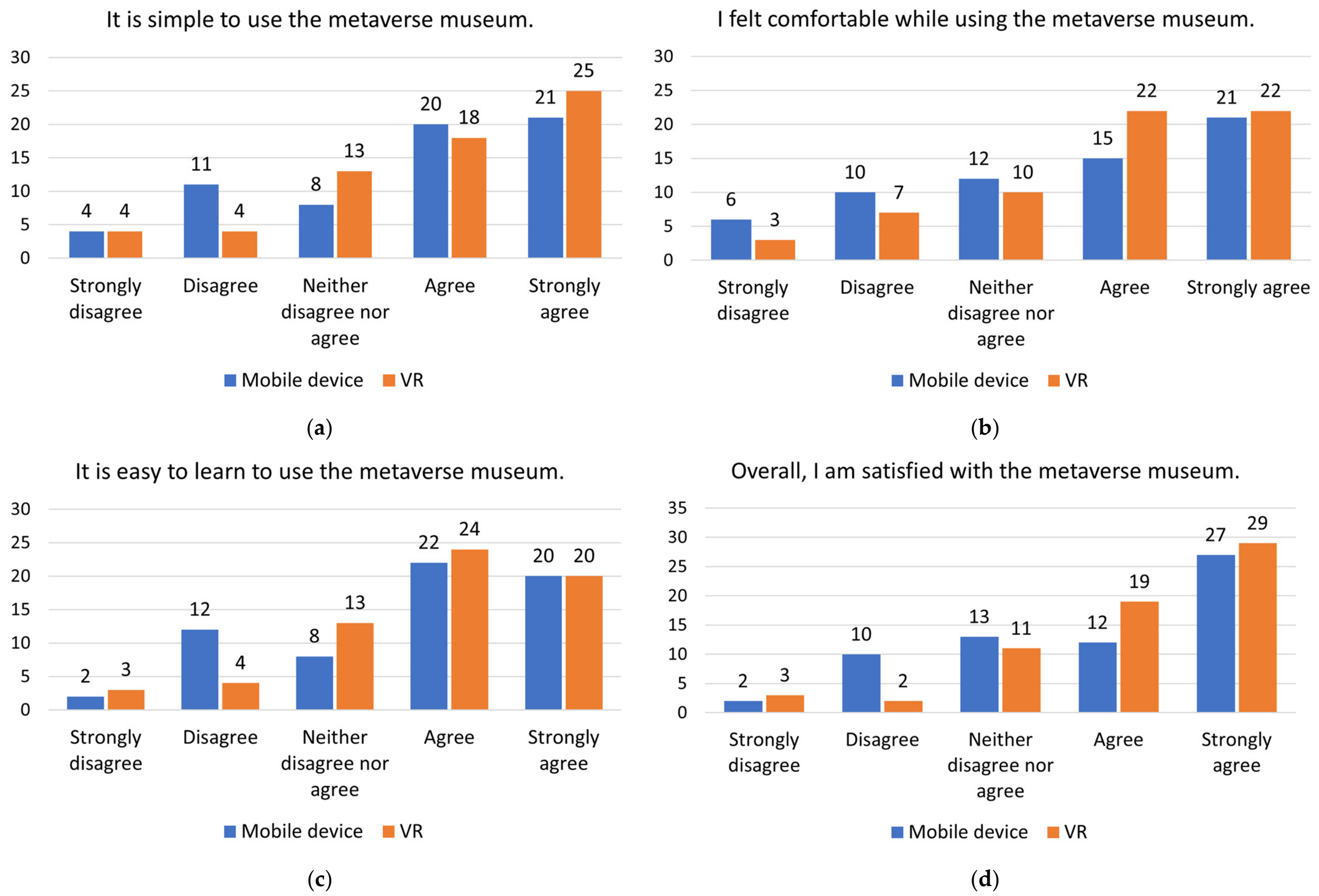


Figure 33. Distributions of participants' ratings for responding to four statements related to the usability of the metaverse museum on the mobile device and in VR: (**a**) Simple use, (**b**) Comfortable to use, (**c**) Easy to learn, and (**d**) Overall satisfaction (N = 64).

Table 3. Descriptive statistics of ratings for statements related to metaverse museum usability on a mobile device and in VR.

	Mean	**Std. Deviation**	**Median**	**95% Confidence Interval**	**N**
It is simple to use the metaverse museum on a mobile device.	3.67	1.27	4	0.31	64
It is simple to use the metaverse museum in VR.	3.88	1.19	4	0.29	64
I felt comfortable while using the metaverse museum on a mobile device.	3.55	1.34	4	0.33	64
I felt comfortable while using the metaverse museum in VR.	3.83	1.16	4	0.28	64
It is easy to learn to use the metaverse museum on a mobile device.	3.72	1.19	4	0.29	64
It is easy to learn to use a metaverse museum in VR.	3.84	1.09	4	0.27	64
Overall, I am satisfied with the metaverse museum on the mobile device.	3.81	1.23	4	0.30	64
Overall, I am satisfied with the metaverse museum in VR.	4.08	1.09	4	0.27	64

4.5.2. Differences in Age Groups

A Mann–Whitney U test was performed to compare ratings of age groups *Young* (N_{young} = 31) and *Adult* (N_{adult} = 33) for all statements and both platforms. The results showed that the ratings of the age groups differ significantly for the next statements:

- Simple to use on a mobile device—the ratings of the young participants were significantly higher than the adult group (Z = −2.916, $p = 0.004$);
- Simple to use in VR—the ratings of the young participants were significantly higher than the adult group (Z = −2.402, $p = 0.016$);
- Comfortable on a mobile device—the ratings of the young participants were significantly higher than the adult group (Z = −2.403, $p = 0.016$);
- Comfortable in VR—the ratings of the young participants were significantly higher than the adult group (Z = −2.129, $p = 0.033$);
- Easy to learn on a mobile—the ratings of the young participants were significantly higher than the adult group (Z = −2.916, $p < 0.001$);
- Overall satisfaction on a mobile device—the ratings of the young participants were significantly higher than the adult group (Z = −3.436, $p < 0.001$);
- Overall satisfaction in VR—the ratings of the young participants were significantly higher than the adult group (Z = −2.534, $p = 0.011$).

4.6. User Experience and Social Aspect

4.6.1. Museum Element Satisfaction

Participants answered questions related to satisfaction with three different elements of the museum: the interior design/environment of the museum, the quality of the artefacts in the virtual museum and the interactivity of the artefacts in the virtual museum. They selected a rating from 1 to 5 where: 1 = Very dissatisfied; 2 = Somewhat dissatisfied; 3 = Neither satisfied nor dissatisfied; 4 = Somewhat satisfied; and 5 = Very satisfied, to express their level of satisfaction with the elements. A distribution of ratings for each element is shown in Figure 34. Descriptive statistics can be observed in Table 4.

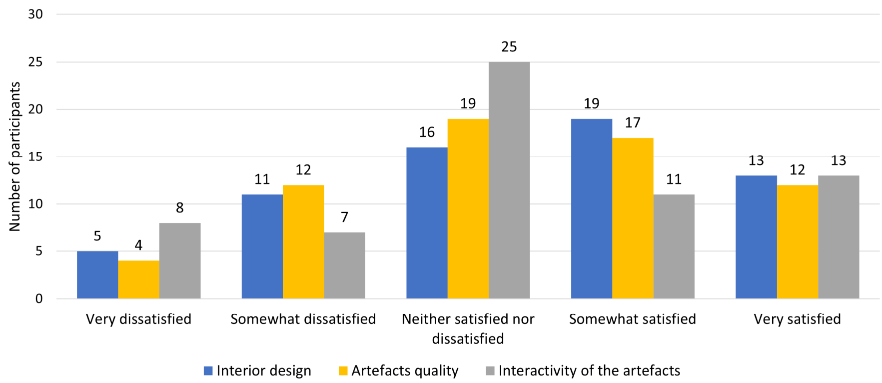


Figure 34. A clustered column chart showing a distribution of participants' ratings for satisfaction with the interior design/environment of the museum, the quality of the artefacts in the virtual museum and the interactivity of the artefacts in the virtual museum (N = 64).

Table 4. Descriptive statistics of ratings for satisfaction with the interior design/environment of the museum, the quality of the artefacts in the virtual museum and the interactivity of the artefacts in the virtual museum.

	Mean	Std. Deviation	Median	95% Confidence Interval	N
Interior design/environment of the museum	3.38	1.21	3.5	0.30	64
Quality of the artefacts in the virtual museum	3.33	1.17	3	0.29	64
Interactivity of the artefacts in the virtual museum	3.22	1.25	3	0.31	64

4.6.2. Overall Enjoyment

Afterwards, participants were asked to respond to ending statements related to the overall satisfaction and user experience of the metaverse museum by choosing a rating from 1 to 5 where: 1 = Strongly disagree; 2 = Disagree; 3 = Neither disagree nor agree; 4 = Agree; 5 = Strongly agree. The statements were related to the overall enjoyment of the metaverse museum, interest in visiting the museum again and recommendation of the metaverse museum to others. A distribution of ratings for each statement is shown in Figure 35. Descriptive statistics can be observed in Table 5.

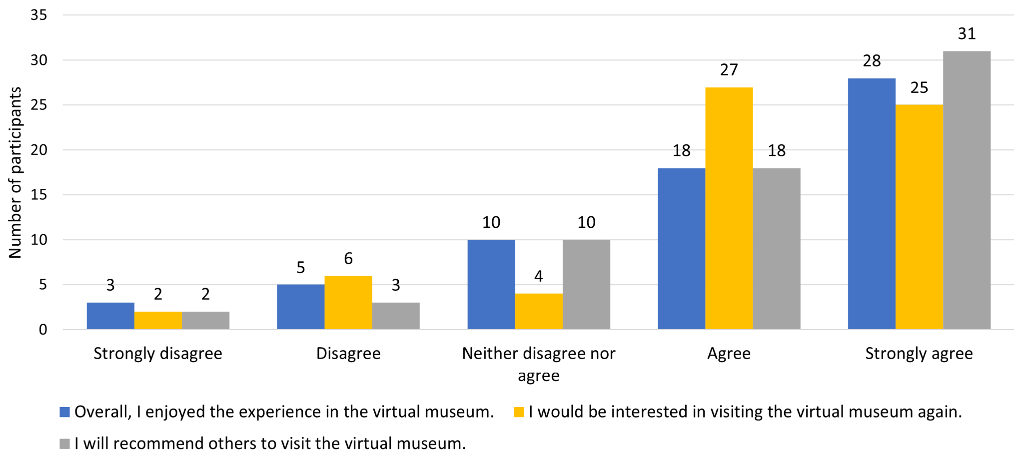


Figure 35. A clustered column chart showing a distribution of participants' ratings for overall enjoyment of the metaverse museum, interest in visiting the museum again and recommendation of the metaverse museum to others (N = 64).

Table 5. Descriptive statistics of ratings for statements related to the overall enjoyment of the metaverse museum, interest in visiting the museum again and recommendation of the metaverse museum to others.

	Mean	Std. Deviation	Median	95% Confidence Interval	N
Overall, I enjoyed the experience in the virtual museum.	3.98	1.16	4	0.28	64
I would be interested in visiting the virtual museum again.	4.05	1.06	4	0.26	64
I will recommend others to visit the virtual museum.	4.14	1.05	4	0.26	64

A Mann–Whitney U test was performed to compare ratings of age groups *Young* (N_{young} = 31) and *Adult* (N_{adult} = 33) for all statements related to the overall experience in the metaverse museum. The results showed that the ratings of the age groups differ significantly for the next statements:

- Overall enjoyment of the metaverse museum—the ratings of the young participants were significantly higher than the adult group ($Z = -2.713$, $p = 0.007$);
- Interest in visiting the museum again—the ratings of the young participants were significantly higher than the adult group ($Z = -2.008$, $p = 0.045$).

4.6.3. Social Aspect

Most of the participants in the experiment visited the metaverse in pairs (one participant on the mobile device and one in VR) or groups (3–4 participants on the mobile and in VR in parallel). Only 5 participants (7.81%) visited the metaverse museum alone and did not encounter other users. We then investigated whether participants liked the ability to interact with other users in the metaverse museum (e.g., to chat or speak with them). A vast number of the participants (78.13%) answered that they liked it, 9.37% responded that they did not like it, and 12.5% responded that they did not know. Results can be observed in Figure 36.

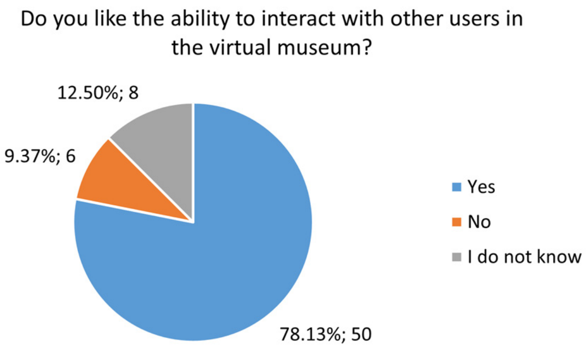


Figure 36. A pie chart showing the distribution of answers related to interaction with other visitors in the metaverse museum (N = 64).

5. Discussion and Future Work

By evaluating the accessibility of a metaverse technological heritage museum prototype described in this work, we have been able to gather insight into how young participants and adults perceive the accessibility of the metaverse museum on mobile and VR platforms and to investigate whether there are any differences in platform preferences between the two age groups. We have also been able to analyse the interaction and navigation techniques provided by Spatial and specify design recommendations for improving the accessibility and inclusivity of metaverse museums as well as for the developers of metaverse environments.

In the evaluation, we focused on two platforms: a mobile device as the most widespread device and a virtual reality headset that enables an immersive and more engaging experience. In addition, we focused on analysing the results based on two user groups. Since young participants (younger than 18 years old) are the usual target group for university museums such as the Telecommunication Museum Vicente Miralles Segarra, we looked at them as one age group, while participants who are 18 or older were considered another age group. This approach allowed us to focus on the specific user needs of a targeted user group, i.e., the young participants, as well as to specify improvements that will address the various needs of users of different ages (from young adults to the elderly), having the universal design in mind.

What emerges from the evaluation results, regardless of a user's age, can be summarized into guidelines for improving the accessibility of the prototype.

One of the three different forms of text appearing in the metaverse museum seems to be more critical in terms of readability than the other two, and that is the text on the posters that conveys important information about the artefacts exhibited in the museum. The options which would make it easier to read the text on the museum artefacts that participants voted for the most were the zoom option, changing the text size, and reading the text aloud (derived from the results presented in Section 4.2.1). The results follow the *Perceivable* principle of the Web Content Accessibility Guidelines (WCAG) 2.2 [29], which can be applied to non-web content as well [62]. In addition, the results confirm the accessibility strategies identified in [20] in the *Perception* category related to visual augmentation, i.e., magnification, large-size text, and audio description. The options and improvements suggested by participants would contribute to text-based museum artefacts by presenting them to users in a way that they can be better perceived. Accessibility features for Meta Quest include adjustment of the text size, but it is only applied for the universal menu and supported Meta Horizon applications [63], which means that those adjustments for the metaverse museum must be implemented in the application.

A similar result was obtained for other types of artefacts (non-textual) for which participants suggested that the zoom option would be beneficial to better observe them (results presented in Section 4.2.2). This is also in line with the accessibility strategy to provide a broad set of visual augmentations identified in [20]). Besides making artefacts perceivable by making them bigger or introducing other modalities, such as sound (for when reading information about them aloud), it is important to consider interaction techniques that are used for suggested options, like the zoom option. Specifically, their ease of use must be considered, especially for people who are interested in observing artefacts in more detail but cannot perform usual zoom actions (e.g., pinch-to-zoom gestures on a mobile device). Introducing alternative methods of interaction to accommodate users who may struggle with usual interaction techniques in these solutions would be beneficial, as well as in line with the WCAG *Operable* principle [29] and the accessibility strategy identified in [20] (support alternative input techniques).

Results for the evaluation of interactable components of the museum (presented in Section 4.2.3), i.e., buttons for selection of different telephony operators, showed that it was not straightforward how to use them or that they even existed for most of the participants. This indicates that this functionality should be more intuitive and comprehensive. The most suggested option for the easier selection of telephony operators is to provide additional instructions on how to select. This is in line with the WCAG *Understandable* principle, especially the *Input Assistance* guideline [29]. The next suggested option is to show all interactable years at once (and not depending on factors such as the position of the avatar). This follows the WCAG *Perceivable* principle, specifically the *Distinguishable* guideline [29], whose goal is to make the default presentation as easy to perceive as possible. The third suggested option is to enable different interaction types for selection besides the one that requires precise hand or aiming interaction (e.g., clicking on a small button on a mobile screen or aiming at a screen and pressing a button on a controller in VR), which is in line with "alternative input techniques" strategy identified in [20].

The teleport portal in the metaverse is a very important feature if one wants to visit different virtual spaces or, in our case, different rooms of a museum. Since this is not a real-world feature, it may cause difficulties for users to understand what needs to be done, as the results showed. The other factor playing an important role in going through the teleport portal with intent is its placement. For example, the avatar's start position needs to be considered, and the portal should be placed in a visible place and not behind the avatar. The most suggested option to facilitate teleporting with intent is to include a confirmation of whether the user wants to teleport to help the user avoid and correct if they selected and walked into a portal by mistake (which is also in line with the *Input Assistance* guideline [29] and the VR game accessibility guideline, according to which the user can confirm or reverse choices they have made [31]). The instruction on how to teleport through a portal is the next suggested option, and this would also help with the understanding of an unfamiliar interaction (in line with the VR game accessibility guideline to include tutorials [31] or the *Input Assistance* guideline [29]). An important suggestion is also to inform users on why to go through the teleport portal, i.e., to provide information about the space/room where the user is teleporting to. This is especially important if a user is offered more than one teleport portal. Accidental teleportation can be corrected if there is an option to go back to the previous room, which is in line with one of the design patterns of Cognitive Accessibility Guidance for reducing barriers experienced by people with cognitive and learning disabilities [64]. These guidelines are derived from the results presented in Section 4.2.4.

The results (presented in Section 4.2.5) confirmed that additional visual or textual guidance in the museum, such as arrows on the floor and information labels, are helpful elements of the metaverse museum (in line with the VR game accessibility guideline to include contextual in-game help/guidance/tips identified in [31]). However, what participants also found helpful was additional information about artefacts by selecting the label, which is an important finding for the museum content. In addition, participants would be interested in getting more information about the interaction with an artefact by selecting the label. While implementing this, it is important not to cover parts of an artefact by the label or text, as emphasized by some of the study participants. This is also in line with one of the accessibility criteria within the WCAG *Perceivable* principle, related to that when content becomes visible on hover or focus, it should not obscure other content [29].

Most of the participants were satisfied with the controls on the mobile device in terms of their size and placement on the screen (results presented in Section 4.3.1). This is offered and implemented by the Spatial, together with the instructions for the controls the user gets upon entering the metaverse application in Spatial for the first time. Unlike mobile devices, users in VR do not get any instructions when they enter the metaverse museum. Participants in the study relied on the instructions given by the researchers before the experiment. Although almost all participants found the headset and the controllers easy to understand and use, they suggested written instructions on how to use the VR controllers to navigate and interact (derived from the results presented in Section 4.4.1). This is in line with the WCAG *Understandable* principle related to providing input assistance [29] and the VR game accessibility guideline to include tutorials [31]. In addition, these instructions should be available at the user's request on both platforms, not just when a user enters the metaverse museum for the first time.

Navigating the metaverse museum was more challenging on both platforms for the adults than for the young participants, according to the ratings for the ease of navigation. This is also reflected in the results for the avatar's speed, where the adults were more likely to perceive it as too fast. These conclusions are derived from the results presented in Sections 4.3.2 and 4.4.2. Suggested options for easier navigation on a mobile device include an easier way of changing the view perspective (currently, touch gestures are used for the camera rotation) as well as slowing down the avatar movement. Some of the participants suggested that it would be beneficial to have buttons instead of a joystick for navigation, which confirms different user preferences and needs regarding interaction techniques (derived from results presented in Section 4.3.2). Having alternative methods of interaction may not just impact better accessibility but also the user experience of the metaverse museum. This is also in line with the design principle related to *customisability* identified in [20].

Suggested options for easier navigation in VR include the *Help* option with information on how to navigate (that can be opened at any time) and instructions on how to navigate and use controllers upon entering a metaverse (derived from results presented in Section 4.4.2). This is in line with the previous result related to the suggestion for making VR equipment easy to understand and use—to have instructions at the beginning as well as available on the user's request, and the guidelines related to input assistance [29] and tutorials [31]. Different types of movement (e.g., teleportation) should also be considered, as some users may prefer it more than moving with a joystick. The customization of the avatar's speed to an individual user or choosing a different type of movement may have an impact on the easier navigation in the metaverse museum on both platforms (in line with *customisability* design principle from [20]).

To help users have better orientation in virtual space, the point of view can be calibrated in VR with the right joystick. Even though some participants did not change their point of view (which also indicates that instructions for controllers are necessary), the results indicate that for most participants, the most comfortable point of view was the point of view from the eyes of the avatar (results presented in Section 4.4.3). However, some participants prefer other points of view, which confirms the importance of different customizations in a metaverse museum (in line with *input redundancy* design principle from [20]). Customizing in general and providing alternatives is important, especially since, for some users, certain interactions in VR may trigger motion sickness and other effects [65]. Some of the study participants reported discomfort during or after the VR experience (result presented in Section 4.4.4). Future work should then include researching the relationship between different settings of the metaverse museum and trigger effects in VR.

If they wanted to get a better view of the artefacts on the mobile device, users could use a pinch-to-zoom gesture or a zoom button that appears at the upper right corner of the screen after clicking on an artefact. The result (presented in Section 4.3.3) showed that the adults found using the pinch-to-zoom gesture more challenging than the younger participants, which may be the result of the way this functionality is implemented—by performing the gesture, the camera view perspective also changes. The alternative was to use a zoom button with which only around half of the participants engaged. Therefore, the interaction with the zoom button should be more intuitive. First, it must be clear that a certain artefact (or parts of the artefact) is interactable—instructions that a zoom button appears when the artefact is clicked on should be provided. Second, the button should be perceivable and placed visually close to the content it influences. This is in line with both the *Perceivable* and *Understandable* principles of the WCAG guidelines [29].

The last-mentioned guidelines can be applied for playing the videos on the mobile device, considering that a lot of participants did not play a video in the metaverse museum due to unawareness of the video playing option and not knowing how to play a video (derived from the results presented in Section 4.3.4). Another guideline in the case of videos is to use a familiar icon for control related to playing the video, i.e., a play icon instead of a plus magnifier icon. This is in line with one of the design patterns of Cognitive Accessibility Guidance [64]. In addition, the suggested option for making the videos easier to perceive is having captions in the same language as the spoken audio, which is in line with the *Perceivable* principle of the WCAG guidelines [29] and the accessibility strategy identified in [20]. According to the results, participants also had an issue with playing the video outside of the metaverse museum, i.e., outside of the Spatial application. First, they needed to download it and then play it with an external video player. This is not in line with the *Predictable* guideline within the WCAG *Understandable* principle [29].

One of the limitations imposed by using Spatial as a metaverse platform is that, in VR, videos cannot be played on their own if they are not set as editable by an administrator of the virtual space. Because this would mean that any participant could have deleted a video with a click (it is not necessary to confirm the deletion), we omitted the investigation of video playing in VR.

Looking at Table 6 with a summary of results that showed significant association or differences between two age groups (young participants and adults) for different dependent variables, we can highlight key differences between young individuals and adults in their experience and perceptions of navigating and interacting with the metaverse museum across different platforms.

Table 6. Summary of findings when comparing significant results between young participants and adults for different elements of the metaverse museum.

	Young	Adults
Teleportation (Section 4.2.4)	more likely to teleport intentionally	more likely that they will not teleport intentionally
Navigation on a mobile device and in VR (Sections 4.3.2 and 4.4.2)	more likely to find it easier to navigate	more likely to find it more difficult to navigate
Avatar speed on a mobile device and in VR (Sections 4.3.2 and 4.4.2)	more likely to find it appropriate	more likely to find it too fast
Pinch-to-zoom gesture on a mobile device (Section 4.3.3)	more likely to use it and find it easier to use	more likely not to use it and find it more difficult to use
Simple to use the metaverse museum on a mobile device and in VR (Section 4.5.2)	more likely to find it simpler to use	more likely to find it more difficult to use
Feeling comfortable while using the metaverse museum on a mobile device and in VR (Section 4.5.2)	more likely to feel more comfortable while using	more likely to feel less comfortable while using
Easy to learn to use the metaverse museum on a mobile device (Section 4.5.2)	more likely to find it easier to learn to use	more likely to find it more difficult to learn to use
Overall satisfied with the metaverse museum on a mobile device and in VR (Section 4.5.2)	more likely to be more satisfied overall	more likely to be less satisfied overall
Overall enjoyment of the metaverse museum experience (Section 4.6.2)	more likely to enjoy the experience more overall	more likely to enjoy the experience less overall
Interest in visiting the metaverse museum again (Section 4.6.2)	more likely to be more interested	more likely to be less interested

The first significant difference is related to the teleportation behaviour, where young participants were more likely to teleport intentionally, whereas adults were less likely to do it on purpose (result presented in Section 4.2.4). This suggests that younger users may be more comfortable with virtual movement mechanics, possibly due to greater familiarity with digital environments and gaming experiences that employ teleportation.

In terms of navigation and interaction, young participants found it easier to navigate both on mobile devices and in VR, whereas adults experienced greater difficulty. Similarly, avatar speed was perceived as appropriate by younger participants but was often considered too fast by adults. These findings (results presented in Sections 4.3.2 and 4.4.2) suggest that adults may require slower movement settings and additional navigation support to enhance their experience.

Regarding gesture-based interactions on a mobile device, young participants were more likely to use and find the pinch-to-zoom gesture intuitively, while adults reported more difficulty or did not use it (result presented in Section 4.3.3). This highlights potential usability challenges for older users, who may not be as accustomed to touch-based interactions commonly used in mobile applications.

Furthermore, results (presented in Section 4.5.2) show that it was more probable that younger participants reported a higher level of agreement for statements indicating that the metaverse museum is simple to use on both platforms, comfortable to use on both platforms and easy to learn to use on a mobile device. In addition, it is more probable that younger participants reported a higher level of agreement for statements indicating overall satisfaction with the metaverse museum on both platforms. The results support the fact that children nowadays are growing up as digital natives and adapt more quickly to new technology interfaces [66].

Finally, differences in overall enjoyment and interest in visiting the metaverse museum again further emphasize the generational divide (derived from results presented in Section 4.6.2). Younger participants expressed greater overall enjoyment of the metaverse museum experience, as well as interest in visiting the museum again. This suggests that user experience improvements, particularly for adults, may be necessary to ensure engagement for a wider audience despite young people being the museum's first target group.

When comparing subjective ratings of all participants for the overall satisfaction with the metaverse museum between the two platforms (result presented in Section 4.5.1), it is more probable to get a higher level of satisfaction in VR than on the mobile device. Even though there are fewer functionalities in the VR metaverse museum than on the mobile device, participants were overall more satisfied with it. This motivates us to further explore how to overcome limitations imposed by the Spatial metaverse platform to introduce missing elements in the VR version of the metaverse museum and to evaluate their accessibility.

Results related to satisfaction with the interior design/environment of the metaverse museum, the quality of the artefacts in the museum and the interactivity of the artefacts in the virtual museum indicate that, in future work, we should also focus on improving those aspects for better user experience and engagement (derived from results presented in Section 4.6.1). This is especially important when considering that the primary target group for the technological heritage university museum in the metaverse are young participants that can improve the learning experience while preserving the museum artefacts by using technologies like augmented and virtual reality, as described in [58].

Responses on statements for overall enjoyment of the metaverse museum, interest in visiting the museum again and recommendation of the metaverse museum to others, where most participants agreed with all statements, encourage us to continue investigating the metaverse concept of the museum (results presented in Section 4.6.2). Since most of the participants also responded that they liked the ability to interact with other users in the metaverse museum, this aspect should be investigated in the future in the context of accessibility as well (result presented in Section 4.6.3).

Results related to accessibility evaluation indicate that there is a need to implement customizable navigation settings, adjustable avatar speeds, alternative interaction methods and different accessibility options to accommodate different user needs in metaverse museums on different platforms. This can be difficult to achieve due to the limitations of existing metaverse platforms such as the one used in this study, i.e., C# scripting in the Spatial Creator Toolkit [59]. This implies future work related to investigating the potential of other metaverse platforms or developing a metaverse museum application from scratch, following the accessibility guidelines and recommendations of improvements resulting from this study.

In the present study, the *Adult* group included participants from a wide range of ages, from young adults to the elderly. As has been explained previously, the *Young* group included the usual target group for the technological heritage university museum (participants younger than 18 years old) and the other participants were analysed together as one age group (*Adult* group). This may have led to variations in responses within the *Adult* group that were not fully captured in the analysis. Future research should recruit a larger and more diverse sample of adult participants, allowing for a more detailed age-based analysis. Furthermore, in this study, 14 participants indicated that they have some form of disability. However, the sample size of representatives for each category of disabilities was not sufficient to draw any conclusions. Therefore, after introducing accessibility improvements in the new version of the metaverse museum, in future work, we intend to include participants with different disabilities to evaluate its inclusivity and how these improvements address their diverse needs in terms of accessibility. Since the universal design approach aims to ensure inclusiveness for users of all abilities, ages, genders, cultural backgrounds, etc., we believe that it would be worth investigating whether gender plays a significant role in shaping accessibility guidelines for metaverse environments in future work. That said, we will aim to balance the gender ratio for future research.

As it is emphasized in [17], there is a significant gap related to the integration of assistive tools in the metaverse environment for accessibility and inclusion. Therefore, future work should include investigating how to incorporate assistive technologies within the Metaverse so that interaction and navigation are facilitated for users with disabilities. Besides investigating the usual assistive technologies people with disabilities use, such as screen readers for the blind and visually impaired, which are essential for their inclusion, it would be an interesting avenue for future research to investigate cutting-edge digital accessibility solutions, such as a virtual walker for wheelchair users that allows users to navigate virtual environments using their natural wheelchair movements, providing haptic feedback based on the terrain they traverse [67] or a wheelchair driving simulator that allows people in wheelchairs to access virtual museum spaces, which are usually inaccessible in reality [68].

Different types of smartphones have been used in the study, which implies variations in screen size and processing power that may have influenced accessibility and overall user experience. In contrast, only one VR headset model (Meta Quest 3) was used, which may limit the generalizability of the findings. Future work should incorporate a wider range of VR headsets, as differences in hardware and controller types could impact ease of interaction, accessibility, and user experience.

6. Conclusions

This study explored the accessibility of a technological heritage museum prototype developed on the Spatial metaverse platform, focusing on user engagement and accessibility across mobile and VR platforms. In an experiment involving 64 participants, we focused on young users as the primary target group for the technological heritage museum and adults to gather a broader perspective on a metaverse museum. The study resulted in specifying accessibility guidelines for metaverse museums and revealing key differences in how young and adult users navigate and interact with virtual museum spaces. Additionally, our findings informed recommendations for improving the current prototype, leading to two main directions for future work.

First, further research should explore enhancements to the existing metaverse museum prototype, recognizing that the use of a specific metaverse platform imposes limitations on modifying certain components, features, and content. Second, future efforts should focus on developing an accessible metaverse museum from scratch, integrating both established accessibility guidelines and the insights specific to technological heritage museums identified in this study.

Developing with accessibility in mind and incorporating inclusive design principles leads to technological solutions that benefit all. Implementing customizable settings related to interaction, navigation, and content appearance in the metaverse museum can help accommodate diverse user needs, remove potential accessibility barriers and enhance overall user experience. As demonstrated by the current prototype based on Spatial, raising awareness of accessibility is essential for metaverse platform developers. Before virtual spaces can be truly open to everyone, accessibility must be a fundamental priority in creating universally inclusive environments.

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Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1 details the questionnaire used for the subjective evaluation of the metaverse museum prototype.

Table A1. Questions for subjective evaluation by sections with answer options.

Section	Question	Options
Demographics	Please specify your gender.	Female; Male; Not binary; Prefer not to say
	Which age group do you belong to?	Under 18; 18-24; 25-34; 35-44; 45-54; 55-64; 65+
	What is the main language you use?	Spanish; Valencian; English; Other
	Have you always lived in Spain, or did you move from another country?	I have always lived in Spain.; I moved from another country to Spain.; Other
	From which country did you move?	(Free-form answer)
	What is the highest degree or level of education you have completed?	Elementary school; Secondary school; Professional degree; Bachelor's degree; Master's degree; Ph.D. or higher; Other
	Please select the statements that apply to you.	I am a person with visual impairments.; I am a person with hearing impairments.; I am a person with motor disabilities.; I am a person with cognitive and neurological disorders.; I am a person with specific learning difficulties.; None of the statements apply to me.
	If you have visual impairments/hearing impairments/motor disabilities/cognitive and neurological disorders/specific learning difficulties, please describe them.	(Free-form answer)
Prior experience with technology	Do you use a smartphone or tablet in your daily life?	Yes; No
	Specify how often you use your smartphone or tablet.	Every day; Several times a week; Several times a month; Several times a year
	Have you experienced any kind of immersive content so far?	Yes; No; I don't know
	Which immersive content have you experienced?	Virtual reality; Augmented reality on the mobile device; Augmented/mixed reality with the smart glasses or headset; 360° video; 360° audio; Haptic content; Other
	How often do you experience or use immersive content?	At least once a day; At least once a week; At least once a month; At least once a year; Only once or twice a year

Table A1. *Cont.*

Section	Question	Options
Usability and accessibility	Is the text that appears in the museum environment easy to read? Is the text that appears as an information label on objects in the museum easy to read? Is the text on the posters in the museum easy to read?	Yes; No
	What would make it easier for you to read the text on the museum artefacts?	Changing the font type; Changing the font size; Changing the colour of the text/background; Make the text simpler or more understandable; Zoom option; Read aloud option; Nothing, it is easy to read; Other
	Are the artefacts that appear in the virtual museum (images, 3D museum objects) big enough in relation to your size (avatar size)?	Yes; No
	What would make it easier for you to better observe museum artefacts?	If museum artefacts were bigger by default; If the size of museum artefacts could be adjusted; If there is a zoom option for all museum artefacts; Nothing, it is easy to observe everything; Other
	How easy is it to select different telephony operators at the manual switching central (i.e., to select different years)?	1 = Very difficult; 2 = Difficult; 3 = Neither difficult nor easy; 4 = Easy; 5 = Very easy
	If you find it difficult to select different telephone operators, what do you think are the reasons for that?	I didn't know how to change to another telephone operator.; I didn't see the option to select any operator.; The display of years kept changing depending on my position.; Other
	What would make it easier for you to select different telephony operators at the manual switching central?	Additional instructions on how to select; Different interaction types used to select; All interactable years shown at once; Nothing, it is easy to select; Other
	Have you teleported (went through a portal) from the first room to another room in the museum intentionally on both platforms (mobile and VR)?	Yes, I teleported on purpose on both platforms.; No, I teleported accidentally in at least one platform.
	What would facilitate teleportation with intent?	Asking to confirm if I want to teleport to another room.; Instructions on how to teleport.; Information on why to teleport/what's in the other room.; If there is the option to come back.; Nothing, it is easy to teleport.; Other
	Are the arrows on the floor indicating the direction of movement through the museum (in the second room) helpful? Is the text on the informative labels on the artefacts helpful and informative (e.g., description of what the object represents)?	Yes; No
	What would informative labels make more helpful and informative?	Selecting the label shows more information about the artefact; Selecting the label shows more information about the possible interaction with an artefact; If they do not cover part of the artefact, i.e., they are placed in another location near the artefact; Nothing, they are informative enough as they are; Other
Mobile device	Which mobile device did you use?	(Free-form answer)
	Are the instructions on how to use the controls on the mobile device (i.e., joystick to move, circle to jump, change the view of the camera) clear and understandable?	Yes; No; I did not get any instructions *
	Are the controls for interaction in the mobile solution big enough (i.e., joystick to move, circle to jump)? Are the controls for interaction in the right place on the screen (i.e., joystick on the left, circle on the right)?	Yes; No
	How easy is it to navigate through the museum on a mobile device?	1 = Very difficult; 2 = Difficult; 3 = Neither difficult nor easy; 4 = Easy; 5 = Very easy
	Is the speed of your avatar when moving on the mobile device appropriate?	Yes, the speed is neither too slow nor too fast.; No, it is too slow.; No, it is too fast.

Table A1. *Cont.*

Section	Question	Options
Mobile device	What would make the navigation in the museum on the mobile device more intuitive and easier?	Having buttons instead of a joystick; Slow down the moving; Easier change of view perspective (rotating the camera); Nothing, navigating is easy; Other
	Have you used the pinch to zoom gesture to get a better view of museum artifacts, i.e., to change the viewing perspective?	Yes; No
	How easy is it to use the pinch-to-zoom gesture to change the view perspective?	1 = Very difficult; 2 = Difficult; 3 = Neither difficult nor easy; 4 = Easy; 5 = Very easy
	Have you used the zoom option (+) to enlarge some images or parts of the poster with text?	Yes; No; I did not see the zoom option.
	Is the content in the museum videos easy to perceive (to see and hear)?	Yes; No; I did not play any videos in the museum.
	What would make it easier for you to perceive the content played in the museum videos?	Captions; Subtitles; Video with audio prerecorded in different languages; Nothing, it was easy to perceive the video content; Other
	What is the reason why you did not play video(s) in the museum?	I didn't know there was an option to play a video.; I didn't know how to play a video.; I didn't want to download a video.; Other
	What would make playing the museum videos on the mobile device easier?	Play videos without downloading them first.; Information that there is a video.; Instructions for playing the video.; Nothing, it was easy to play the videos.; Other
	It is simple to use the virtual museum on a mobile device. I feel comfortable while using the virtual museum on a mobile device. It is easy to learn to use a virtual museum on a mobile device. Overall, I am satisfied with the virtual museum on the mobile device.	1 = Strongly disagree; 2 = Disagree; 3 = Neither disagree nor agree; 4 = Agree; 5 = Strongly agree.
Virtual reality	Do you find the VR equipment (headset and controllers) easy to understand and use?	Yes; No
	Would it be helpful to have written instructions when entering a virtual museum on how to use the VR controllers to navigate and interact?	Yes; No; I don't know
	How easy is it to navigate through the museum in virtual reality?	1 = Very difficult; 2 = Difficult; 3 = Neither difficult nor easy; 4 = Easy; 5 = Very easy
	Is the speed of your avatar when moving in virtual reality appropriate?	Yes, the speed is neither too slow nor too fast.; No, it is too slow.; No, it is too fast.
	What would make the navigation in a virtual reality museum more intuitive and easier?	Instructions on how to navigate and use controllers at the beginning; Having the Help option with instructions that can be opened any time; Possibility of different ways of movement, e.g., teleportation; Nothing, navigating is easy; Other
	Have you switched between different camera points of view, i.e., between your avatar's eye view and when the camera is behind your avatar?	Yes; No; I don't know
	What point of view is the most comfortable for you?	View from the eyes of the avatar; View from behind the avatar but close to the avatar; View from behind the avatar but far away from avatar
	Have you felt discomfort or motion sickness while using a VR application?	Yes; No
	Please describe the discomfort.	(Free-form answer)
	It is simple to use the virtual museum in VR. I feel comfortable while using the virtual museum in VR. It is easy to learn to use a virtual museum in VR. Overall, I am satisfied with the virtual museum in VR.	1 = Strongly disagree; 2 = Disagree; 3 = Neither disagree nor agree; 4 = Agree; 5 = Strongly agree.

Table A1. *Cont.*

Section	Question	Options
Socialization and User Experience	Please select the platform you initially used to explore the virtual museum.	Mobile device; Virtual reality headset
	Did you encounter other users (visitors) in the virtual museum?	Yes; No
	Would you like the possibility of interacting with other users in the virtual museum (e.g., to chat or speak with them)?	Yes; No; I don't know
	How satisfied are you with: Interior design/environment of the museum Quality of the artefacts in the virtual museum The interactivity of the artefacts in the virtual museum	1 = Very dissatisfied; 2 = Somewhat dissatisfied; 3 = Neither satisfied nor dissatisfied; 4 = Somewhat satisfied; 5 = Very satisfied
	Overall, I enjoyed the experience in the virtual museum. I would be interested in visiting the virtual museum again. I will recommend others to visit the virtual museum.	1 = Strongly disagree; 2 = Disagree; 3 = Neither disagree nor agree; 4 = Agree; 5 = Strongly agree.
	Were there any technical issues during your visit (e.g., loading problems, navigation problems, etc.)? Do you have any recommendations for improving the virtual museum experience on both mobile and VR platforms?	(Free-form answer)

* Instructions are given only to the user entering the Spatial on the mobile device for the first time.

References

1. Stephenson, N. *Snow Crash: A Novel*; Random House Publishing Group: New York, NY, USA, 2003. Available online: https://www.penguinrandomhouse.com/books/172832/snow-crash-by-neal-stephenson/ (accessed on 13 November 2024).
2. Founder's Letter, 2021. Meta. Available online: https://about.fb.com/news/2021/10/founders-letter/ (accessed on 13 November 2024).
3. Rospigliosi, P.A. Metaverse or Simulacra? Roblox, Minecraft, Meta and the turn to virtual reality for education, socialisation and work. *Interact. Learn. Environ.* **2022**, *30*, 1–3. [CrossRef]
4. Schroeder, R. *Possible Worlds: The Social Dynamic of Virtual Reality Technology*; Westview Press, Inc.: Boulder, CO, USA, 1996.
5. Rymaszewski, M. *Second Life: The Official Guide*; John Wiley & Sons: Hoboken, NJ, USA, 2007.
6. VRChat. Available online: https://hello.vrchat.com (accessed on 13 November 2024).
7. Roblox Corporate. Available online: https://corp.roblox.com/ (accessed on 13 November 2024).
8. Han, J.; Liu, G.; Gao, Y. Learners in the Metaverse: A systematic review on the use of roblox in learning. *Educ. Sci.* **2023**, *13*, 296. [CrossRef]
9. Wang, H.; Ning, H.; Lin, Y.; Wang, W.; Dhelim, S.; Farha, F.; Ding, J.; Daneshmand, M. A survey on the Metaverse: The state-of-the-art, technologies, applications, and challenges. *IEEE Internet Things J.* **2023**, *10*, 14671–14688. [CrossRef]
10. Tlili, A.; Huang, R.; Shehata, B.; Liu, D.; Zhao, J.; Metwally, A.H.S.; Wang, H.; Denden, M.; Bozkurt, A.; Burgos, D.; et al. Is Metaverse in education a blessing or a curse: A combined content and bibliometric analysis. *Smart Learn. Environ.* **2022**, *9*, 24. [CrossRef]
11. *11. ISO 9241-210:2019 (en)*; Ergonomics of Human-System Interaction—Part 210: Human-Centred Design for Interactive Systems. International Organization for Standardization (ISO). Available online: https://www.iso.org/obp/ui/#iso:std:iso:9241:-210:ed-2:v1:en (accessed on 15 January 2021).
12. Fox, D.; Thornton, I.G. The IEEE Global Initiative on Ethics of Extended Reality (XR) Report–Extended Reality (XR) Ethics and Diversity, Inclusion, and Accessibility. In *The IEEE Global Initiative on Ethics of Extended Reality (XR) Report—Extended Reality (XR) Ethics and Diversity, Inclusion, and Accessibility*; IEEE: New York, NY, USA, 2022; pp. 1–25.
13. Longo, M.C.; Faraci, R. Next-generation museum: A Metaverse journey into the culture. *Sinergie Ital. J. Manag.* **2023**, *41*, 147–176. [CrossRef]
14. Wu, R.; Gao, L.; Lee, H.; Xu, J.; Pan, Y. A study of the key factors influencing young users' continued use of the digital twin-enhanced Metaverse museum. *Electronics* **2024**, *13*, 2303. [CrossRef]
15. Abilkaiyrkyzy, A.; Elhagry, A.; Laamarti, F.; Saddik, A.E. Metaverse key requirements and platforms survey. *IEEE Access* **2023**, *11*, 117765–117787. [CrossRef]
16. Zallio, M.; Clarkson, P.J. Designing the metaverse: A study on inclusion, diversity, equity, accessibility and safety for digital immersive environments. *Telemat. Inform.* **2022**, *75*, 101909. [CrossRef]

17. Othman, A.; Chemnad, K.; Hassanien, A.E.; Tlili, A.; Zhang, C.Y.; Al-Thani, D.; Altınay, F.; Chalghoumi, H.; Obeid, M.; Altınay, Z.; et al. Accessible Metaverse: A theoretical framework for accessibility and inclusion in the Metaverse. *Multimodal Technol. Interact.* **2024**, *8*, 21. [CrossRef]
18. Yin, L.; Dudley, J.J.; Garaj, V.; Kristensson, P.O. An online survey assessing the accessibility barriers encountered by users of virtual and augmented reality. In Proceedings of the 2024 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW), Orlando, FL, USA, 16–22 March 2024; IEEE Computer Society: Washington, DC, USA; pp. 330–334. [CrossRef]
19. Creed, C.; Al-Kalbani, M.; Theil, A.; Sarcar, S.; Williams, I. Inclusive AR/VR: Accessibility barriers for immersive technologies, Univers. *Access Inf. Soc.* **2024**, *23*, 59–73. [CrossRef]
20. Dudley, J.; Yin, L.; Garaj, V.; Kristensson, P.O. Inclusive Immersion: A review of efforts to improve accessibility in virtual reality, augmented reality and the metaverse. *Virtual Real.* **2023**, *27*, 2989–3020. [CrossRef]
21. Radanliev, P.; De Roure, D.; Novitzky, P.; Sluganovic, I. Accessibility and inclusiveness of new information and communication technologies for disabled users and content creators in the Metaverse. *Disabil. Rehabil. Assist. Technol.* **2024**, *19*, 1849–1863. [CrossRef] [PubMed]
22. Shao, D.; Lee, I.-J. Acceptance and influencing factors of social virtual reality in the Urban elderly. *Sustainability* **2020**, *12*, 9345. [CrossRef]
23. Baker, S.; Kelly, R.M.; Waycott, J.; Carrasco, R.; Hoang, T.; Batchelor, F.; Ozanne, E.; Dow, B.; Warburton, J.; Vetere, F. Interrogating social virtual reality as a communication medium for older adults. *Proc. ACM Hum. -Comput. Interact.* **2019**, *3*, 1–24. [CrossRef]
24. Abendschein, R.; Desai, S.; Astell, A.J. Towards accessibility guidelines for the Metaverse: A synthesis of recommendations for people living with Dementia. In Proceedings of the Conference on Human Factors in Computing Systems (CHI'23), Workshop Towards an Inclusive and Accessible Metaverse, Hamburg, Germany, 23–28 April 2023. [CrossRef]
25. Zhang, K.; Deldari, E.; Lu, Z.; Yao, Y.; Zhao, Y. It's just part of me: Understanding avatar diversity and self-presentation of people with disabilities in social virtual reality. In Proceedings of the 24th International ACM SIGACCESS Conference on Computers and Accessibility, New York, NY, USA, 23–26 October 2022; ASSETS '22; pp. 1–16. [CrossRef]
26. Zhang, K.; Deldari, E.; Yao, Y.; Zhao, Y. A Diary Study in Social Virtual Reality: Impact of Avatars with Disability Signifiers on the Social Experiences of People with Disabilities. In Proceedings of the 25th International ACM SIGACCESS Conference on Computers and Accessibility, New York, NY, USA, 23–25 October 2023; ASSETS '23; pp. 1–17. [CrossRef]
27. Steed, A. Three technical challenges of scaling from social virtual reality to metaverse(s): Interoperability, awareness and accessibility. *Front. Virtual Real.* **2024**, *5*, 1432907. [CrossRef]
28. Accessibility In The Metaverse, Metaverse Standards Forum. Available online: https://metaverse-standards.org/domain-groups/accessibility-in-the-metaverse/ (accessed on 28 February 2025).
29. Web Content Accessibility Guidelines (WCAG) 2.2, W3C Web Accessibility Initiative (WAI). Available online: https://www.w3.org/TR/WCAG22/#operable (accessed on 26 February 2025).
30. Park, G.; Dreamson, N. *Guidelines to Assess Inclusion and Accessibility in Metaverse Standard Development*; Technical Report ITU FGMV-03; International Telecommunication Union (ITU)-T: Geneva, Switzerland, 2023. Available online: https://www.itu.int/dms_pub/itu-t/opb/fg/T-FG-MV-2023-03-PDF-E.pdf (accessed on 15 April 2025).
31. Heilemann, F.; Zimmermann, G.; Münster, P. Accessibility guidelines for VR games-A comparison and synthesis of a comprehensive set. *Front. Virtual Real.* **2021**, *2*, 697504. [CrossRef]
32. Vlahovic, S.; Skorin-Kapov, L.; Car, Z. An Initiative Toward an Enhanced Industry-Reported Comfort, Accessibility, and Safety Rating System for VR Applications. In Proceedings of the 2023 15th International Conference on Quality of Multimedia Experience (QoMEX), Ghent, Belgium, 20–22 June 2023; pp. 95–98. [CrossRef]
33. Meta Horizon OS Developers. Accessibility, Meta Horizon. Available online: https://developers.meta.com/horizon/design/accessibility/ (accessed on 28 February 2025).
34. Parker, C.; Yoo, S.; Fredericks, J.; Tran, T.T.M.; Williamson, J.R.; Lee, Y.; Woo, W. Building a metaverse for all: Opportunities and challenges for future inclusive and accessible virtual environments. In Proceedings of the Extended Abstracts of the 2024 CHI Conference on Human Factors in Computing Systems, New York, NY, USA, 11–16 May 2024; CHI EA '24; pp. 1–5. [CrossRef]
35. Accessibility Toolkit For Unity, Devpost. Available online: https://devpost.com/software/accessibility-toolkit-for-unity (accessed on 19 November 2024).
36. Zhao, Y.; Cutrell, E.; Holz, C.; Morris, M.R.; Ofek, E.; Wilson, A.D. SeeingVR: A set of tools to make virtual reality more accessible to people with low vision. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, New York, NY, USA, 4–9 May 2019; CHI '19; pp. 1–14. [CrossRef]
37. Collins, J.; Jung, C.; Jang, Y.; Montour, D.; Won, A.S.; Azenkot, S. The guide has your back: Exploring how sighted guides can enhance accessibility in social virtual reality for blind and low vision people. In Proceedings of the 25th International ACM SIGACCESS Conference on Computers and Accessibility, New York, NY, USA, 22–25 October 2023; ASSETS '23; pp. 1–14. [CrossRef]

38. Trewin, S.; Hanson, V.L.; Laff, M.R.; Cavender, A. PowerUp: An accessible virtual world. In Proceedings of the 10th international ACM SIGACCESS conference on Computers and accessibility, New York, NY, USA, 13–15 October 2008; Assets '08; pp. 177–184. [CrossRef]
39. Hutson, J.; Hutson, P. Museums and the Metaverse: Emerging Technologies to Promote Inclusivity and Engagement. In *Application of Modern Trends in Museums*; IntechOpen: London, UK, 2023; Faculty Scholarship. Available online: https://digitalcommons.lindenwood.edu/faculty-research-papers/452 (accessed on 15 April 2025).
40. Barreto-Paredes, C.; Agudo, D.; Granda, M.F.; Parra, O. Evaluating extended reality application for a Virtual museum. Case study: Remigio crespo museum. In Proceedings of the 2022 Third International Conference on Information Systems and Software Technologies (ICI2ST), Quito, Ecuador, 8–10 November 2022; pp. 49–56. [CrossRef]
41. Alabau, A.; Fabra, L.; Martí-Testón, A.; Muñoz, A.; Solanes, J.E.; Gracia, L. Enriching user-visitor experiences in digital museology: Combining Social and virtual interaction within a Metaverse environment. *Appl. Sci.* **2024**, *14*, 3769. [CrossRef]
42. Roblox Corporation. The Replica. Available online: https://www.roblox.com/game-details-web-subsite/games/13745860159/The-Replica (accessed on 28 February 2025).
43. The Vordun Museum and Gallery, Second Life. Available online: https://secondlife.com/destination/vordun-museum-and-gallery (accessed on 28 February 2025).
44. Falcon, A.; Portelli, B.; Abdari, A.; Serra, G. Paving the way for personalized museums tours in the Metaverse. In Proceedings of the IRCDL 2024: 20th conference on Information and Research science Connecting to Digital and Library Science, Brixen, Italy, 22–23 February 2024; CEUR Workshop Proceedings. Available online: https://www.semanticscholar.org/paper/Paving-the-Way-for-Personalized-Museums-Tours-in-Falcon-Portelli/f1c1e9e18b2d0aff8e97025c60dcfd59a25b78c8 (accessed on 27 November 2024).
45. Cecere, L.; Colace, F.; Gupta, B.B.; Lorusso, A.; Messina, B.; Valentino, C. Metaverse and museum: A case study. *Procedia Struct. Integr.* **2024**, *64*, 2189–2196. [CrossRef]
46. Chomjan, S.; Wannapiroon, P.; Nilsook, P. Intelligent metaverse museum based on the universal design to enhance immersive learning experiences. In *2023 Research, Invention, and Innovation Congress: Innovative Electricals and Electronics (RI2C)*; IEEE: New York, NY, USA, 2023; pp. 83–87. [CrossRef]
47. Koukopoulos, D.; Koukoulis, K.; Sylaiou, S.; Fidas, C. XR technologies fostering museum visits for people with impairments. In Proceedings of the First International Workshop on Accessibility and Multimodal Interaction Design Approaches in Museums for People with Impairments Co-Located with MobileHCI 2023 Conference, Athens, Greece, 26 September 2023; CEUR Workshop Proceedings. Fidas, C., Sylaiou, S., Kuflik, T., Liarokapis, F., Koutsabasis, P., Wallace, M., Koukopoulos, D., Antoniou, A., Mania, K., Lykourentzou, I., Eds.; Volume 3622, pp. 17–25. Available online: https://ceur-ws.org/Vol-3622/#paper3 (accessed on 7 October 2024).
48. Caldarelli, A.; Tore, S.D.; Ceccacci, S.; Todino, M.D.; Campitiello, L.; Giaconi, C. Co-designing Immersive and Inclusive Virtual Museum with children and People with Disabilities: A Pilot Study. In Proceedings of the 2022 International Conference on Computational Science and Computational Intelligence (CSCI), Las Vegas, NV, USA, 14–16 December 2022; IEEE Computer Society: Washington, DC, USA, 2022; pp. 1964–1969. [CrossRef]
49. Zou, C.; Rhee, S.-Y.; He, L.; Chen, D.; Yang, Y. Sounds of history: A digital twin approach to musical heritage preservation in virtual museums. *Electronics* **2024**, *13*, 2388. [CrossRef]
50. Triviño-Tarradas, P.; Mohedo-Gatón, A.; Carranza-Cañadas, P.; Hidalgo-Fernandez, R.E. The application of Metaverse in the tourism sector as a tool for enhancing sustainability—Case study: A medieval 'Perfume Burner' of the local historical museum of Montilla (Cordoba, Spain). *Sustainability* **2024**, *16*, 6966. [CrossRef]
51. Lee, J.; Bae, J.; Bae, Y. Implementation of a Gamification-Based Metaverse Exhibition: A Case Study of the Farewell Museum. *Sustainability* **2024**, *16*, 6212. [CrossRef]
52. Buragohain, D.; Meng, Y.; Deng, C.; Li, Q.; Chaudhary, S. Digitalizing cultural heritage through metaverse applications: Challenges, opportunities, and strategies. *Herit. Sci.* **2024**, *12*, 295. [CrossRef]
53. Srdanović, P.; Skala, T.; Maričević, M. InHeritage—A gamified mobile application with AR and VR for cultural heritage preservation in the Metaverse. *Appl. Sci.* **2025**, *15*, 257. [CrossRef]
54. Tamarit Núñez, P.T. Migration to META Platform of the Virtual Reality Environment of the Telecommunications Museum Vicente Miralles Segarra. Bachelor's Thesis, Universitat Politècnica de València, València, Spain, 2024.
55. Unity Technologies, Real-Time Development Platform 3D, 2D, VR & AR Engine, Unity. Available online: https://unity.com (accessed on 28 February 2025).
56. Spatial-Create Immersive UGC, Virtual Classrooms, Experiential Marketing, Spatial. Available online: https://www.spatial.io/ (accessed on 28 February 2025).
57. Vicente Miralles Segarra Telecommunication Museum. Available online: https://museotelecomvlc.webs.upv.es/vicente-miralles/ (accessed on 28 February 2025).

58. Bachiller, C.; Monzo, J.M.; Rey, B. Augmented and virtual reality to enhance the didactical experience of technological heritage museums. *Appl. Sci.* **2023**, *13*, 3539. [CrossRef]
59. Spatial Creator Toolkit-Powered by Unity. Available online: https://toolkit.spatial.io (accessed on 28 February 2025).
60. Polycam Inc. Polycam 3D Scanner, LiDAR, 360, App Store. Available online: https://apps.apple.com/us/app/polycam-3d-scanner-lidar-360/id1532482376 (accessed on 28 February 2025).
61. Sketchfab-The Best 3D Viewer on the Web, Sketchfab. Available online: https://sketchfab.com (accessed on 28 February 2025).
62. Guidance on Applying WCAG 2 to Non-Web Information and Communications Technologies (WCAG2ICT), W3C Web Accessibility Initiative (WAI). Available online: https://www.w3.org/TR/wcag2ict-22/ (accessed on 10 February 2025).
63. Accessibility Features for Meta Quest, Meta. Available online: https://www.meta.com/en-gb/help/quest/674999931400954/ (accessed on 28 February 2025).
64. Let Users Go Back, W3C Web Accessibility Initiative (WAI). Available online: https://www.w3.org/WAI/WCAG2/supplemental/patterns/o4p02-back-undo/ (accessed on 26 February 2025).
65. W3C Web Accessibility Initiative (WAI), XR Accessibility User Requirements. Available online: https://www.w3.org/TR/xaur/ (accessed on 20 December 2020).
66. Taherian Kalati, A.; Kim, M.S. What is the effect of touchscreen technology on young children's learning?: A systematic review. *Educ. Inf. Technol.* **2022**, *27*, 6893–6911. [CrossRef]
67. Riera, J.V.; Palma, B.; Casanova-Salas, P.; Pérez, M.; Gimeno, J.; Fernandez, M. Development and evaluation of a haptic virtual walker for wheelchair users in immersive VR environments. *Appl. Sci.* **2025**, *15*, 23. [CrossRef]
68. Gonzalez, D.O.; Berrocal, I.J.I.; Eugenio, G.A.S.; Morales, A.M.; Leo, V.D.; Sánchez, A.P. Inclusion VR: A new virtual reality device for inclusive experiences. In *Re-Imagining Higher Education through Equity, Inclusion and Sustainability (RISE)*, 2nd ed.; EUt+ Academic Press: Dublin, Ireland, 2022. [CrossRef]