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A Metaverse Platform for Preserving and Promoting Intangible Cultural Heritage

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Abstract: The metaverse, powered by XR technologies, enables human augmentation by enhancing physical, cognitive, and sensory capabilities. Cultural heritage sees the metaverse as a vehicle for expression and exploration, providing new methods for heritage fruition and preservation. This article proposes a metaverse application, inspired by the events of the Italian Resistance, promoting interactions between multiple users in an immersive VR experience while safeguarding intangible cultural assets according to an edutainment approach. The virtual environment, based on Ivrea's town hall square, provides in-depth information about the partisan's life and the historical value of its actions for the city. Furthermore, the application allows users to meet in the same virtual place and engage with one another in real time through the Spatial SDK. Before the public presentation, a heterogeneous group of thirty users underwent usability and engagement tests to assess the experience on both VR headsets and smartphones. Tests revealed statistically significant evidence that there is a genuine difference in users' perceptions of usability and engagement with different devices and types of interaction. This study highlights the effectiveness of adopting XR as a supporting technology to complement the real experience of cultural heritage valorization.

Keywords: cultural heritage; digital heritage; edutainment; metaverse; virtual reality

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1. Introduction

The metaverse concept has evolved significantly since its first mention in Neal Stephenson's 1992 science fiction novel *Snow Crash*, in which it was portrayed as a Virtual Reality-based successor to the Internet [1]. It has been shaped by decades of technological developments and is now being driven by the rapid development of Extended Reality (XR) technologies. Nowadays, the metaverse defines a virtual, immersive, collective, and shared space that results from the convergence of physical reality, virtual elements, and the Internet. Users within the metaverse are represented by avatars and can interact with one another and with 3D digital objects, experiencing life in ways they could not in the physical world [2].

The fast growth of these technologies as well as additional crucial elements, like appropriate bandwidth, interoperability standards, and the integration of AI, blockchain, and cryptocurrencies, are moving the metaverse even further forward [3]. These technologies not only supply the infrastructure required to construct realistic virtual worlds, but they also make these places interactive, safe, and commercially feasible.

The metaverse is also enabling the employment of a truly human-centered approach, fostering human augmentation by providing users with new ways to interact with and experience digital settings. The expression "Augmented Humans" [4] refers to the adoption of methods and technology that enhance physical, cognitive, or sensory skills beyond what is common for humans. This paradigm shift is transforming various aspects of daily life and industries, such as education [5] and healthcare [6], by providing immersive learning environments, virtual training simulations, and new forms of entertainment.

Indeed, XR technologies, including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), act as gateways to the metaverse notion, making it more feasible and accessible by allowing the creation of detailed, immersive, and, most importantly, interactive virtual environments. VR offers experiences comparable to jumping into another world, allowing one to explore and interact with these environments by immersing users in fully digital environments, which will eventually be designed on the basis of the actual world [7]. AR, on the other hand, superimposes digital content on the real environment, enhancing users' perception of reality with additional features and virtual objects in order to provide "augmented" information for better comprehension of the surrounding space [8]. The seamless integration of digital aspects into the physical environment encourages new forms of interaction and engagement, blurring the boundaries between the virtual and the real. MR goes a step further in this sense, seamlessly integrating the virtual and physical worlds, allowing digital objects to interact with real-world environments and vice versa [9]. The result is an immersive experience where users can simultaneously modify and interact with physical and digital elements.

Together, these XR technologies establish a foundation for the metaverse by enabling the creation of complex, interactive virtual environments that users can live in and explore. Developing XR environments for cultural heritage involves overcoming technical hurdles in several areas. Challenges include acquiring and preserving high-quality content through advanced imaging technologies, like photogrammetry and LiDAR scanning, and performing adequate data processing and optimization crucial to ensure visually appealing and performant XR models [10], achieved through mesh reconstruction and polygon reduction. Interactivity and immersion are enhanced by incorporating features like realistic physics simulations and dynamic lighting effects. Considering the variety of visualization devices, cross-platform compatibility is essential for guaranteeing full accessibility, as well as intuitive UI/UX design, which will eventually include gesture-based controls and spatial audio cues, aiming to facilitate easy navigation and engagement. Finally, performance optimization minimizes latency and input lag to prevent motion sickness, while providing accessibility and inclusivity through features such as text readability and support for assistive technologies ensures that XR experiences are enjoyable and educational for all users [11,12]. As these technologies improve and become more accessible, the metaverse concept becomes more tangible, opening up limitless possibilities for creativity, cooperation, and new forms of social interaction [13]. In this scenario, it is not surprising that cultural heritage (CH) has been found to be fertile ground for the adoption of the metaverse as an innovative tool for expression and investigation [14] since novel opportunities to experience the rich legacy of the past in ways that were previously unimaginable have been created.

The capability of users to communicate with one another is a vital element of the metaverse, adding an entertaining dimension to the educative nature of cultural venues [15]. Users can cooperate, share their experiences, explore virtual replicas of historic sites, and sometimes contribute to the cultural narrative, making the metaverse a dynamic and participatory environment. The seamless integration of AR and VR technologies enables different forms of user engagement, offering various levels of immersiveness and interactivity that can enhance the educational and entertainment value of heritage sites, eventually blending into the same "edutainment" approach [16]. Multi-user AR experiences enable people to collaborate and engage with digital content simultaneously, generating a sense of community and shared exploration. These experiences rely on client–server architectures that enable users to "enter" the same AR environment, allowing for real-time communication and synchronization among users, ensuring that everyone visualizes the same AR content and interacts seamlessly with one another [17–20]. While AR allows for the creation of interactive experiences in real-world scenarios, in VR the metaverse expresses its maximum potential, since the full sensory immersion provided by VR technology fosters a strong sense of presence and connection among users, enhancing the impact of shared experiences in the metaverse. The capacity to create shared virtual environments where users may interact, communicate, and cooperate in real time opens up a world of possibilities for entertainment, education, and social involvement. Tangible cultural assets typically benefit from VR visual and spatial capabilities, which allow users to immerse themselves in detailed replicas of historical sites or artifacts. The current literature presents several examples of 3D reconstructions of lost, inaccessible, or protected heritage sites using digital technologies [10–12,21–24], as well as digital replicas of museum halls and artifacts [25–27], becoming multi-user environments in which exploration and learning become a social experience.

Although tangible heritage is generally prioritized for its visual attractiveness and accessibility, efforts to foster intangible culture are equally essential for preserving traditions and practices [28]. Intangible cultural assets include practices, representations, expressions, stories, and skills that communities recognize as part of their cultural heritage. The metaverse offers a unique platform for documenting, digitizing, and dynamically presenting these aspects, assuring their preservation and continued relevance [29]. The current literature contains very few examples of the metaverse being used to enrich intangible historical material. Among these, Fan et al. [28] developed an information service platform about the historic figure of Zhu Xi, the founder of Neo-Confucianism, that includes metaverse functionalities to provide personalized services adaptable to the different tourists' needs, while Lee et al. [30] developed a web application that allows students to virtually meet at the United Nations Memorial Cemetery in Korea and engage in a virtual memorial ceremony on memory Day, 11 November, to honor fallen United Nations veterans.

In this context, this article explores the potential of a metaverse VR application inspired by the events of the Italian Resistance, in particular the commemoration of Italy's liberation from Nazism, the end of the Nazi occupation, and the definitive fall of the fascist regime, promoting interactions between multiple users in an immersive VR experience. An investigation of users' feedback is carried out to comprehend whether a metaverse enabled by Virtual Reality could be a viable solution to safeguard intangible cultural heritage. Moreover, the developed application also investigates the impact of multi-user interactions throughout the experience. The recent literature highlights how this feature can be considered an added value for increasing the level of immersivity and provides benefits for the overall user experience [15,31]. In this sense, our platform was conceived as a multi-user application in order to strengthen immersivity and presence, which would have been compromised if the considered square was empty, as this condition is far from the real one. This approach aims to enhance the accessibility of the experience and information retrieval to people connected remotely for several reasons, including disabilities and physical distance from the location, represented through the virtual environment. Such a characteristic is also core to give greater visibility to the actual location and event, especially among younger people.

Although the metaverse could be enabled by different XR technologies, VR was selected as the most suitable choice for our application, due to the need to recreate the same location in the past (1944) and increasing immersivity and presence during the experience. Our VR application is presented as a 3D digital archive of historical facts, where users can engage with the past in an educational and transformative way, delving into the events that characterized the partisan Resistance against the fascist dictatorship and German occupation. The application includes metaverse social interaction features through the Spatial SDK, allowing users to meet as avatars in the same virtual location, chat, and engage with one another in real time. Furthermore, it enables the preservation and transmission of the intangible cultural assets associated with the Resistance, ensuring that these are not forgotten by future generations.

This paper is organized as follows: Section 2 describes our platform's organization, explains our development decisions, and discusses the rationale behind them. Section 3 presents and analyzes the obtained results. Finally, Section 4 draws the conclusions.

2. Materials and Methods

In the first of the following subsections, a brief explanation of Ferruccio Nazionale's significance to the partisan struggle is provided. Then, the following subsection describes the metaverse platform's implementation, focusing not only on the technical implementation but also on the rationale behind the design, which aimed to value Nazionale's memory through an innovative, immersive experience.

2.1. Case-Study: The History of Ferruccio Nazionale

The anniversary of the Liberation of Italy is an Italian national day, which is celebrated every 25 April, to commemorate the liberation of Italy from Nazi-Fascism, the end of the Nazi occupation, and the final fall of the fascist regime. It is a significant day in the history of Italy as a symbol of the Resistance and the struggle waged by the partisans and the army.

One of the most significant episodes was the summary execution of the Garibaldian partisan Ferruccio Nazionale, also known as "Carmela", whose body, immortalized in a macabre photo, has become one of the symbols of the ferocity reached during the civil war. On the morning of 29 July 1944, in Ivrea (Turin, Italy), Don Augusto Bianco, a military chaplain close to the Nazi-Fascist 10th MAS Division, walked down the street, imparting blessings on passersby. Ferruccio Nazionale, one of them, suddenly pulled a bomb from their jacket but was promptly stopped by a soldier before he could detonate it. The fascists rushed at him, began beating them up, then took them to the barracks, where they continued to assault the dying young man, finally hanging the corpse in the town hall square. The man's body was left hanging with a sign around his neck, which has become an iconic image due to a photo taken by a rifleman; it should have remained in the town square as a warning to the community, which had been forced to gather and parade in front of the corpse. At the end of the conflict, the Italian Republic honored Nazionale with the Bronze Medal for Military Valour in Memory.

2.2. The Metaverse Platform

The platform was designed to provide users with an immersive, interactive, and multi-user experience, as well as the opportunity to explore local history and immerse themselves in the details of Ferruccio Nazionale's life, the Resistance, and the events that profoundly influenced the city of Ivrea.

The virtual environment traces the square of Ivrea's town hall, which is named after Ferruccio Nazionale. Several Points of Interest (POIs) are identified within it, which serve as a hub for detailed information on Ferruccio Nazionale's life and the historical and cultural context associated with the Resistance period, as well as the city of Ivrea's significant contribution during that time. Each POI is intended to present users with information and curiosities related to the history of Ferruccio Nazionale and their symbolic role in the Resistance, as well as to contextualize historical events within the local reality of Ivrea.

To integrate the metaverse features into the virtual environment, a Spatial Creator Toolkit Standard Development Kit (SDK) was used. This toolkit offers a series of powerful tools for building metaverse experiences, enabling developers to incorporate multi-user and communication capabilities into virtual environments so that immersive and collaborative experiences in which users can interact meaningfully with one another and with the virtual content can be developed. With multi-user capability, users can join and interact in the virtual environment at the same time, allowing for collaborative and social activities as well as communication via text chat and emojis. Furthermore, we selected this toolkit because of its flexibility to support a wide range of devices, including VR headsets and more conventional devices like mobile phones, tablets, and desktop computers. This flexibility makes the virtual experience more accessible, allowing more individuals to join the experience.

The virtual environment of Ivrea's town hall square was modeled using the open-source software Blender (version 3.5), which provides extensive capabilities for modeling, texturing, and animating 3D objects.

The many components of the square were constructed in Blender, including architectural structures, urban details, and landscape aspects, to ensure realism and historical accuracy. An example of building modeling in Blender can be seen in Figure 1.

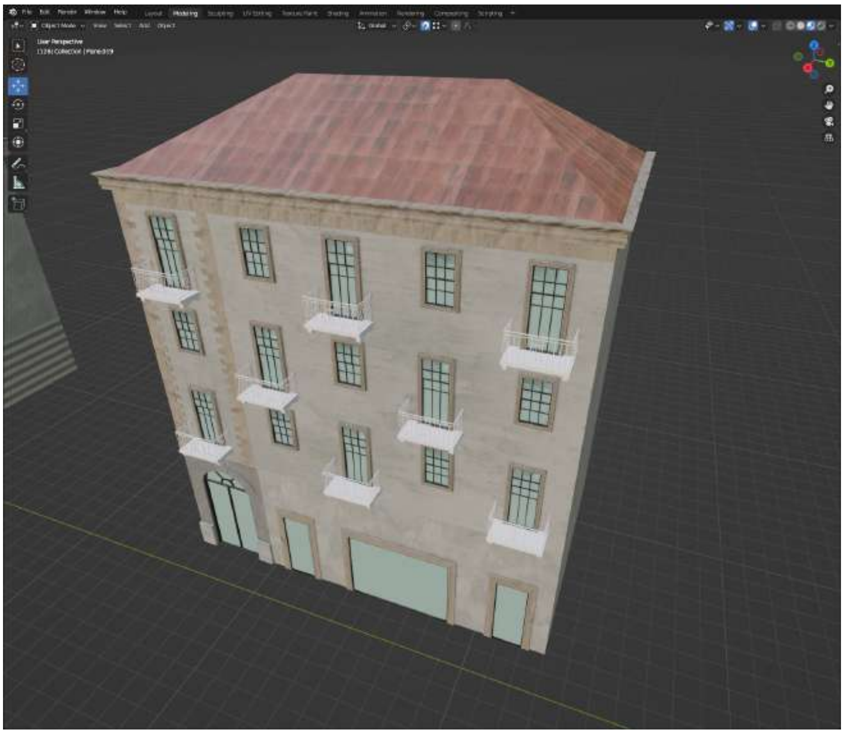

Figure 1. Blender building 3D model.

We chose to model two different scenes of the town hall square, both as it appears today and as it actually appeared during the Resistance period. This approach adds a level of depth and understanding to the narrative and allows users to fully immerse themselves in the past, providing context and relevant details about the circumstances that characterized those events.

During the modeling phase, a compromise had to be achieved between the Spatial SDK's requirements and the necessity for an accurate representation of the global environment. This required carefully weighing the number of vertices used to model the surfaces to guarantee an appropriate level of detail for the models while adhering to the restrictions given by the Spatial SDK's performance requirements. Another critical feature that necessitated careful consideration was the correct application of textures. Again, a compromise had to be made between the requirements of using Spatial SDK to avoid overloading the Spatial gaming hub, and so ensuring a smooth user experience, and the necessity to retain high visual quality at the same time. The main goal was to encourage interactivity and user participation by allowing users to explore and interact with the virtual environment without facing technical difficulties or limits while preserving a visually appealing representation of the entire area. As a result, the decision to adopt tileable textures nevertheless preserved high levels of visual detail to create an interactive and fluid multi-user experience. This decision was made to guarantee a positive engagement and user interaction experience while minimizing slowdowns or performance concerns that could jeopardize the entire experience. By implementing these optimization strategies, the environment was successfully prepared for efficient loading and seamless integration into the Spatial gaming hub.

The whole 3D environment was then exported from Blender and imported into Unity 3D, a well-known game engine that provides advanced functionality for creating interactive experiences and virtual environments.

Spatial SDK was then imported and configured into the Unity project, providing the necessary components for developing metaverse functionality. This included the ability for users to create their own virtual avatar, interact with 3D objects and scene elements, navigate between different areas of the virtual world, and interact with other users in real time through text chat and emojis.

Using Unity, it was possible to implement the POIs within the virtual environment, which enhanced the cultural value of the metaverse platform. Indeed, the addition of POIs not only increased the educational value of the application but also encouraged players to explore and learn more about the rich historical context surrounding Ferruccio Nazionale and the city of Ivrea during the Resistance period. These POIs served as focal points within the virtual environment, offering users the opportunity to delve into specific aspects of history and culture related to Ivrea during the Resistance. Users could engage with these POIs through interactive features and access detailed information on Ferruccio Nazionale's life, the Resistance movement, and Ivrea's main historical events through multimedia content, textual information, and immersive experiences tailored to each POI.

Eight POIs are located within the two scenes of the application. In particular, four POIs are related to the significance of the 25 April celebrations and the repercussions these events had on the present day in the contemporary scene, while the four POIs referring to the figure of Ferruccio Nazionale and the historical events related to their life were placed in the contextualized scene, namely the scene during the period of the Resistance. A POI distribution map in the virtual environment can be seen in Figure 2.

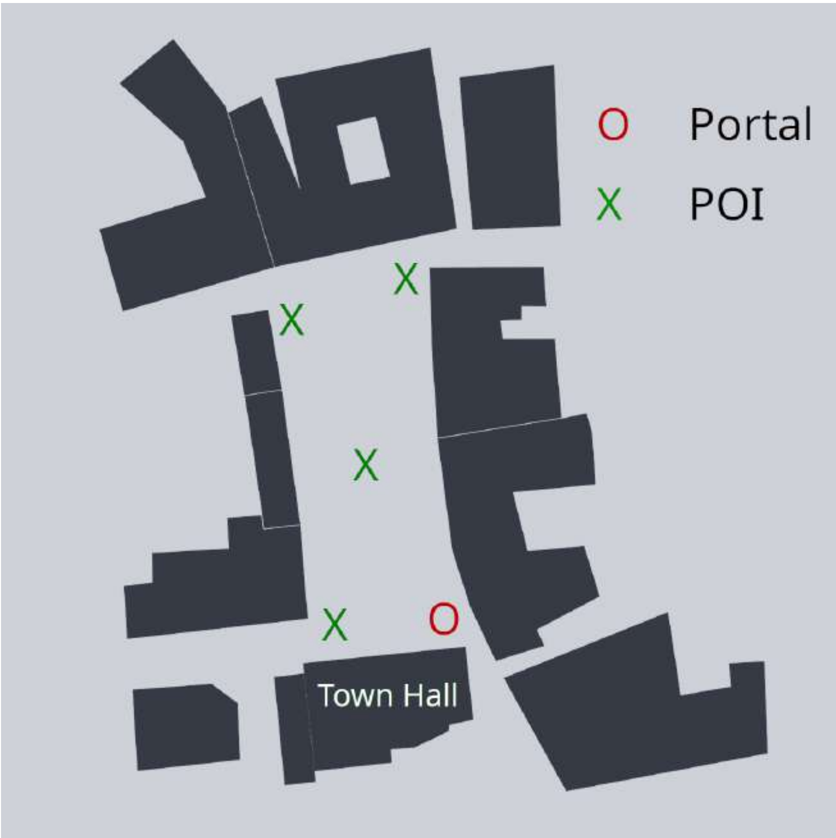

Figure 2. Virtual environment map with the representation of the Points of Interest (POIs) and the portal for access from the contemporary scene to the contextualized scene and the way back. The POIs are located in the same places within the two scenes, with four in each.

Additionally, in the contextualized scene, we included an accurate representation of the scaffold on which Ferruccio Nazionale's body was executed in the center of the square (Figure 3). This decision was made with the aim of providing users with an authentic and reflective experience, as if they were among the people present that day, allowing for full comprehension of the context and impact of the historical events depicted. Moreover, two portals were included in each environment, allowing users to "teleport" from one scene to the other, adding an element of interactivity to the overall experience. These portals can be conceived as virtual access points that allow users to move fluidly from one representation of the square to the other, thus making the exploration of the two historical periods extremely accessible and engaging.

Figure 3. An example of a POI in the VR environment. The details of the scaffold in the contextualized scene were captured by the Unity 3D game engine.

The process of developing an immersive educational experience centered around Ferruccio Nazionale's historical legacy required a rigorous methodological approach to assure the authenticity and completeness of the information presented. To confirm the validity and accuracy of the information obtained, a multidisciplinary team was established, including experts in modern Italian history and partisan Resistance. The research relied on primary sources, like direct testimonies, historical records, and photographic archives regarding Ferruccio Nazionale, as well as secondary sources, like academic publications, biographies, and historical studies on the Italian Resistance. Every piece of information gathered was carefully reviewed to ensure that it was consistent with Ferruccio Nazionale's historical and cultural background, with a focus on details that accurately described their person and role in the Resistance.

The selected information was subsequently adapted to provide an immersive experience within the VR environment, taking into account user engagement methods and optimizing the visual presentation of Ferruccio Nazionale's history.

After the environment was configured and finalized, it went through a phase of testing to ensure that all functionalities worked properly and that the user experience was optimal. After the completion of testing with different devices, including Meta Quest 2, Meta Quest Pro, laptops, tablets, and smartphones, the environment was published on the 3D Spatial game hub (Figure 4). This publishing process made the environment accessible for web, mobile, and VR users via a wide range of devices, including laptops, tablets, smartphones, and VR headsets.

Figure 4. Metaverse platform on Spatial. View of the VR environment in the contemporary scene with the access portal in the background.

3. Results and Discussion

Usability and engagement tests were performed on the developed metaverse application in order to identify the strengths and weaknesses of the platform. Usability refers to the ease and satisfaction with which users interact with the interface of a website or application. A more usable interface has various benefits, including improved information accessibility and comprehension, simplified content memorization and learning, and more user autonomy and security when using the product. On the other hand, user engagement refers to the level of a user's cognitive, temporal, and behavioral involvement when interacting with a digital system.

Given the historical meaning of this event and the expectation of a wide and heterogeneous audience, these evaluations were carefully developed to determine how people from various backgrounds and demographics would engage with and navigate the application. A heterogeneous group of thirty participants, representing a wide range of backgrounds and demographics, spanning ages 21–63 and different education levels, was actively involved in the testing process. The intentional inclusion of this diversity provided a thorough evaluation across a wide range of potential users who will participate in the metaverse experience during the celebrations. The participants were further separated into two evenly distributed groups: headset users, who tested the experience with the Meta Quest Pro VR headset, and smartphone users, who tested the experience using a smartphone. The participants from both groups underwent a preliminary training phase to become familiar with the commands used for navigation and interaction within the virtual environment. The distinction allowed us to evaluate if the experience could be perceived differently when using devices with different levels of immersion and different interaction modalities.

To analyze the application's usability, the System Usability Scale (SUS) was utilized, which is a standardized test consisting of ten questions designed to investigate a platform's ease of use. The System Usability Scale (SUS) is the most commonly used standardized survey for evaluating perceived usability. It has been extensively adopted in several different domains since its inception in the 1980s to the present day, proving to be a solid measure of perceived usability [32]. Each questionnaire item can be answered with five response options, ranging from one, "Strongly agree", to five, "Strongly disagree". The participants' scores for each question were then converted into a new number that could vary from 0 to 100, as described by Brook et al. in [33]. According to studies, an SUS score of 68 or higher is regarded as above average, while anything less than 68 is considered below average [34].

To assess user engagement, the User Engagement Scale (UES) questionnaire in its short form was administered to participants. The User Engagement Scale (UES) has been considered one of the most used approaches to assess user engagement (UE) in a variety of digital domains [35]. The same research highlighted the need for a briefer questionnaire, which led to the User Engagement Scale-Short Form (UES-SF) to avoid some issues arising when comparing UES answers across different applications. Consequently, we decided to adopt the UES-SF to meet a balanced trade-off between the accuracy and the robustness of the results in order to facilitate comparisons with future applications in the cultural heritage domain. Furthermore, in this case, participants had to rate their degree of agreement or disagreement on a five-point scale with each of the twelve items in the questionnaire. The total engagement score, ranging from one to five, was then determined by aggregating all the elements and dividing by twelve, as described in [35].

The participants were asked to download the Spatial application onto their own devices and create their profile and avatar to represent themselves. All of them received a brief explanation of the purpose of the platform, its functionalities, and the necessary instructions for interacting within the environment with objects and other users. They then received access to the immersive metaverse experience by connecting to a specific web URL. After entering the experience, they were left free to explore the environment and engage in the experience for as long as they desired, before completing the questionnaires at the conclusion of the experience.

For both groups, the median was used to indicate the central tendency of the answers to a certain test question for the selected group, while the dispersion was determined by comparing the lowest and highest values. The questionnaire items and aggregated results are reported in Table 1 for the SUS and in Table 2 for the UES.

Table 1. User testing questions for the SUS assessment. The aggregate questionnaire findings are presented in terms of median, minimum, and maximum values.

Item	Questionnaire Item	VR Headset			Smartphone		
		Min	Median	Max	Min	Median	Max
1	I think that I would like to use this system frequently.	3	4	5	3	4	4
2	I found the system unnecessarily complex.	1	2	2	1	2	2
3	I thought the system was easy to use.	3	5	5	5	5	5
4	I think that I would need the support of a technical person to be able to use this system.	1	2	3	1	1	2
5	I found the various functions in this system were well integrated.	3	4	5	4	5	5
6	I thought there was too much inconsistency in this system.	1	1	2	1	1	2
7	I would imagine that most people would learn to use this system very quickly.	3	4	5	4	5	5
8	I found the system very cumbersome to use.	2	2	3	1	1	2
9	I felt very confident using the system.	3	4	5	4	4	5
10	I needed to learn a lot of things before I could get going with this system.	1	2	3	1	1	2

As regards the results obtained from the SUS questionnaire, participant scores were transformed into the final SUS score, resulting in a median value of 75, a minimum value of 55, and a maximum value of 87.5 for the VR headset group, and a total SUS score ranging from 70 to 97.5, with a median of 92.5 for the smartphone group. Wilcoxon's rank sum test was used to compare the SUS values between the two groups to determine whether there were any statistically significant differences in perceived usability based on whether the users used a VR headset or a smartphone. We found a test statistic below the critical value corresponding to a significance level of 5% (p-value = 0.007), which means that there is a significant difference in the perceived usability between the two groups, with higher usability for the smartphone groups when compared to the VR headset group. There might be several reasons why the group using smartphones had greater perceived usefulness than the group using the VR headset. Among the potential causes, users' familiarity with the device could lead them to feel more at ease when using an application on a common device such as a smartphone rather than a VR headset, hence favorably affecting their perceived usability. Furthermore, using a VR headset involves the use of controllers or physical movements for navigating the virtual environment, whereas smartphones may be managed by touch and more familiar gestures. This difference in physical interaction, combined with other factors such as the device's visual quality or comfort, may impact users' perceptions of usability, with an overall preference for a more conventional interface.

In terms of engagement, the participants' scores were combined to produce the final UES score, with the VR headset group obtaining a median value of 4.58, a minimum value of 3.42, and a maximum value of 4.92, while the smartphone group received a minimum value of 3, a maximum value of 4.68, and a median value of 3.83. The results indicate that the VR headset group had greater engagement levels than the smartphone group. The median UES score for the VR headset group is higher than that for the smartphone group, indicating that VR headset users were more engaged with the application than smartphone users.

Table 2. User testing questions for the UES assessment. The aggregate questionnaire findings are presented in terms of median, minimum, and maximum values. The sign "*" in the "Item" column is used to highlight items with a reversed scale.

Item	Questionnaire Item	VR Headset			Smartphone		
		Min	Median	Max	Min	Median	Max
1	I lost myself in this experience.	3	4	5	2	3	4
2	The time I spent using this Application just slipped away.	4	5	5	2	4	5
3	I was absorbed in this experience.	3	4	5	1	3	4
4*	I felt frustrated while using this Application.	3	4	5	4	4	5
5*	I found this Application confusing to use.	3	4	4	4	4	4
6*	Using this Application was taxing.	3	4	5	4	4	5
7	This Application was attractive.	4	5	5	4	4	5
8	This Application was aesthetically appealing.	3	4	5	3	4	5
9	This Application appealed to my senses.	3	4	5	2	3	4
10	Using this Application was worthwhile.	4	5	5	4	5	5
11	My experience was rewarding.	3	4	5	3	4	5
12	I felt interested in this experience.	4	5	5	3	5	5

To validate the statistical significance of these differences, the Wilcoxon rank sum test was repeated to see whether the statistical significance was sufficient to conclude that there was a statistically significant difference in engagement levels between the two groups. We obtained a test statistic that is less than the critical value for a significance level of 5% (p-value = 0.048), indicating that there is a significant difference in the degree of engagement between the two groups, with the VR headset group showing a higher level of engagement with respect to the smartphone group. Users belonging to the VR headset group achieved higher engagement scores than those who used smartphones possibly due to the greater immersiveness offered by VR headsets, which provide a more immersive experience than smartphones, allowing users to feel more involved and engaged in the virtual environment compared to the relatively constrained interaction offered by smartphones Furthermore, we cannot exclude the novelty effect of VR technology, which means that some users may be unfamiliar with VR headsets, stimulating their interest and engagement during their first interactions with the app.

Our findings are consistent with prior research. Litvak et al. [36], for example, performed similar analyses on their AR-based smart guide and found that, in terms of usability, the SUS results showed a significantly more favorable rating for their smartphone guide than their headset guide. This aligns with our findings, demonstrating that smartphones provide a more user-friendly interface for accessing cultural heritage information than VR headsets. In terms of engagement, some studies indicate a preference for systems with more interactivity and immersion capabilities, such as VR headsets. For example, research evaluating the same experience on different XR systems discovered that systems with more interactivity and immersion were preferred over others [37]. This result highlights the potential for VR headsets to create a more immersive and engaging experience while visiting cultural heritage sites. The preference for immersive experiences is also reflected in the finding that, although being more cumbersome than smartphones, VR headsets create a stronger sense of presence in users [38]. This increased sense of presence can improve total immersion and the emotional connection to the cultural content of the exhibition, thus leading to a more meaningful experience for visitors.

SUS items can be subdivided into four categories: learnability, efficiency, ease-of-use, and satisfaction. The obtained answers suggest that the smartphone-related learning curve is faster than the HMD one, with a superior ease-of-use due to higher familiarity with the device; on the other hand, HMDs provide a more engaging experience. These considerations are qualitative insights that can complement the quantitative analysis reported above; in fact, the SUS is designed to provide a single overall score representing the system's usability, and breaking it down into subdivisions may reduce the reliability and interpretability of the results. On the other hand, UES items can be classified into focused attention (items 1–3), perceived usability (items 4–6), aesthetic appeal (items 7–9), and reward factor (items 10–12). In this sense, according to the median results, HMDs foster users' attention and are more aesthetically appealing; the perceived smartphone usability is slightly better than that for HMDs, in line with the SUS questionnaire answers, while the reward factor can be considered the same for both technologies.

The unique strengths of smartphones and VR headsets in terms of usability and engagement have significant consequences for the cultural heritage sector's growth. While smartphones may provide an easy entry point for people to connect with cultural heritage information, VR headsets give a more in-depth and immersive experience that may lead to a greater understanding and knowledge of heritage.

Cultural venues may exploit the broad usability and familiarity of users with smartphones to provide a simple and accessible way for visitors to engage with cultural information, without the logistical challenges and expenses involved with the distribution and maintenance of more advanced equipment such as VR headsets. This convenience also applies to guests, who may access the site content using their own devices, increasing their experience without the need for extra supplies or support.

On the other hand, VR headsets offer a level of immersion and presence that is unmatched by smartphones. This immersive experience allows users to feel as if they are actually present at the heritage site or historical environment being explored. Furthermore, VR headsets can make users experience places that may be inaccessible or no longer exist in the physical world, such as ancient ruins or historical monuments destroyed over time, providing new opportunities for preserving cultural heritage, particularly for individuals who are unable to visit these locations in person. Although the initial setup and cost of VR equipment are significantly higher than those of smartphones, technological advancements are gradually making VR more accessible and affordable. As VR devices become more widely available, cultural venues and organizations may include more VR experiences in their offerings to supplement traditional exhibitions.

By using both technologies' distinct capabilities, the cultural heritage sector may successfully reach and engage a wide range of people, promoting better respect for and knowledge of historical legacies.

4. Conclusions

This study shows the potential of XR technologies as strong tools for improving the exploration, fruition, and preservation of cultural heritage through the metaverse. We demonstrated the ability of XR to create immersive and interactive experiences that overcome physical limitations by developing and implementing a metaverse VR application inspired by events linked to the Italian Resistance, allowing users to engage with historical narratives in new and meaningful ways.

The proposed platform could be a replicable use case in other contexts for cultural heritage valorization. Obviously, realizing a tailored solution requires modifications in terms of virtual model creation, which is strongly environment-dependent, to guarantee the accuracy and veracity of the reproductions. Nonetheless, the approach of inserting Points of Interest throughout a virtual environment, whether they are plain texts or other interactive elements, and trying to make it as immersive as possible with the presence of other users, not only by realizing photorealistic 3D models, can be adopted for those situations where visitors need to access a cultural site remotely or would like a complement experience to their live visits.

Our findings highlight the value of XR in enabling real-time multi-user interactions and enhancing their engagement level inside virtual environments, supporting collaborative exploration and knowledge sharing across heterogeneous audiences. Usability and engagement test findings support the usefulness of XR in eliciting positive user experiences and enabling deeper immersion in cultural heritage environments. Future work is going to consolidate these results by designing and developing other platforms for the valorization of both intangible and tangible cultural heritage with a focus on adopting a user-centered approach aimed at realizing experiences tailored to users' profiles and preferences.

By adopting XR as a complementary tool to traditional approaches to heritage understanding and preservation, it becomes possible to develop new opportunities for storytelling, education, and community participation while protecting intangible cultural assets for generations to come.

Future research should be tailored to the employed VR device in order to realize human-centered solutions and provide personalized experiences. HMDs provide a higher level of immersivity compared to traditional visualization systems but still suffer from some issues that are limiting their spread. First, users can perceive a certain discomfort in terms of wearability or VR motion sickness due to a mismatch between what the eyes see in the virtual environment and what the inner ear and body feel in the real world; to minimize this condition, VR solutions should include a training phase to adapt the end user to increasingly longer sessions. Second, technology development is mandatory to improve the HMDs' autonomy, especially in those scenarios requiring consecutive sessions, for instance, a training context or avoiding queues of visitors in a museum. Moreover, an interesting approach that is taking hold is blending VR and AR in a single device. This choice is paving the way for the design of flexible solutions capable of optimizing the management of the interaction between the real and the virtual world, improving the visual feedback, enhancing the user experience, and thus focusing the applications on the individuals according to a truly human-centered approach.

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