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Review

A framework study on the use of immersive XR technologies in the cultural heritage domain

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ABSTRACT

Most cultural promotion and dissemination are nowadays performed through the digitization of heritage sites and museums, a necessary requirement to meet the new needs of the public. Augmented Reality (AR), Mixed Reality (MR), and Virtual Reality (VR) have the potential to improve the experience quality and educational effect of these sites by stimulating users' senses in a more natural and vivid way. In this respect, head-mounted display (HMD) devices allow visitors to enhance the experience of cultural sites by digitizing information and integrating additional virtual cues about cultural artifacts, resulting in a more immersive experience that engages the visitor both physically and emotionally.

This study contributes to the development and incorporation of AR, MR, and VR applications in the cultural heritage domain by providing an overview of relevant studies utilizing fully immersive systems, such as headsets and CAVE systems, emphasizing the advantages that they bring when compared to handheld devices. We propose a framework study to identify the key features of headset-based Extended Reality (XR) technologies used in the cultural heritage domain that boost immersion, sense of presence, and agency. Furthermore, we highlight core characteristics that favor the adoption of these systems over more traditional solutions (e.g., handheld devices), as well as unsolved issues that must be addressed to improve the guests' experience and the appreciation of the cultural heritage.

An extensive search of Google Scholar, Scopus, IEEE Xplore, ACM Digital Library, and Wiley Online Library databases was conducted, including papers published from January 2018 to September 2022. To improve review reporting, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were used. Sixty-five papers met the inclusion criteria and were classified depending on the study's purpose: education, entertainment, edutainment, touristic guidance systems, accessibility, visitor profiling, and management.

Immersive cultural heritage systems allow visitors to feel completely immersed and present in the virtual environment, providing a stimulating and educational cultural experience that can improve the quality and learning purposes of cultural visits. Nonetheless, the analyzed studies revealed some limitations that must be faced to give a further impulse to the adoption of these technologies in the cultural heritage domain.

1. Introduction

Recently, a growing number of studies have highlighted the advantages of using immersive reality technologies and Human-Computer Interaction (HCI) methods for knowledge dissemination in the cultural heritage domain [1]. Although there is still a need to investigate the limitations of such technologies, such as the lack of real-time and consistent tracking and registration techniques [2], or the need to naturalize user interaction in such applications [3], Extended Reality (XR) technologies are on the rise in the field of virtual heritage and are now widely adopted in museums, heritage sites, and archaeological sites around the world. Indeed, the digitization of cultural sites and museums plays a significant role in the promotion and dissemination of culture, and it is now required to meet new public needs [4].

Augmented Reality (AR), Mixed Reality (MR), and Virtual Reality (VR) can enhance the visitor's experience by increasing sensations [5], emotions [6], cognition [7], and skills [8] when compared to

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the real world. Virtual information is integrated into the real environment by means of smart devices such as handheld devices, head-mounted displays (HMDs), and space displays [9], although mobile devices such as handheld devices and HMDs are preferred for cultural applications [10].

Cultural heritage applications based on mobile XR devices enable visitors to deepen their knowledge and enhance their experience of cultural sites by being able to digitize information and merge virtual information about cultural artifacts, like texts, animations, models, and audio in the real world. From the individual user's perspective, these technologies when used in cultural sites really have the potential to improve experience quality and educational effect, stimulating their senses more naturally and vividly [11].

The use of MR, AR, and VR through handheld devices does not realize its full potential. The use of smartphones and tablets allows visitors to instantly access a wealth of information, reach points of interest (POIs), or obtain further information and suggestions on specific attractions but requires a momentary interruption of the visiting experience to access the handheld device [12]. On the other hand, using HMDs such information can be provided directly in the user's field of view, ensuring a seamless and uninterrupted experience.

Recently, a significant number of low-cost immersive reality headsets have appeared on the market with improved graphics capabilities, location sensors, and rendering. Therefore, immersive reality headsets and HCI methods are being used in the field of cultural heritage to enhance education, exploration, and exhibitions. These advances could move traditional museums and cultural venues towards the installation of immersive reality technologies, changing visitors' expectations and the future design of cultural experiences.

The remainder of this paper is structured as follows: Section 2 illustrates the main objectives of this paper, Section 3 describes the methods for selecting and organizing scientific papers relevant to the review's purpose. Section 4 provides an overview of the included studies. Section 5 addresses a broad range of benefits and current challenges in the world of XR headset-based applications for cultural heritage, and Section 6 draws conclusions.

2. Research aim

For the above-mentioned reasons, in this review, we focus on applications in the cultural heritage domain using immersive XR systems such as headsets and Cave Automatic Virtual Environment (CAVE) systems, in which the immersivity, sense of presence, and agency reach their highest expression [13]. As a result, our aim is to answer the following research questions:

RQ1: Which kind of applications involving XR headsets and CAVE systems are currently employed in the cultural heritage domain?
RQ2: What advantages and limitations characterize immersive XR headsets compared to more traditional handheld technologies when involved in cultural heritage applications?
RQ3: Which task-specific design, development, and usability issues arise from XR headset-based cultural heritage applications?

Therefore, a framework study is proposed to identify the key features of headset-based AR/MR/VR technologies, and the relationship between these technological aspects and the visitor's experience, determining whether there are core attributes that favor the adoption of these systems over traditional solutions, and unsolved issues that need to be addressed to give a further impulse to the inclusion of these technologies in the cultural heritage domain.

3. Material and methods

3.1. Literature search

The goal of this analysis was to determine which categories of cultural heritage applications already use XR headsets, as well as what advantages and issues were found in this area. The purpose of the data collection procedure was to garner a collection of works with the potential to address the research questions under consideration.

The following electronic databases were thoroughly searched to retrieve the published research articles: Google Scholar, Scopus, IEEE Xplore, ACM Digital Library, and Wiley Online Library. The online digital libraries search has been performed by two reviewers in September 2022. To focus on the most recent advances in this field, the search is limited by publication year: only English-language articles published between January 2018 and September 2022, inclusive, were taken into account for our research.

The following keywords were employed when searching for articles: Cultural Heritage; Culture; Museum; Museums; Digital culture; Digital Museum; Virtual Museum; Augmented Reality; Virtual Reality; Mixed Reality; Extended Reality; Immersive technologies; Headset; Head-Mounted-Display; Smart glass. All the research terms were individually or collectively examined. Terms with similar concepts were aggregated with “OR” to collect a comprehensive list of articles, while “AND” was used to relate technological solutions and the domain of interest.

3.2. Selection process

The current complies with the Preferred Reporting Items on Systematic Reviews and Meta-analysis (PRISMA) standards. Searching for pertinent documents in the databases, chosen on the basis of their relevance to our work, we took into account specific inclusion and exclusion criteria. The inclusion criteria are provided in the following list:

- Papers have been published between January 2018 and September 2022 inclusive;
- Papers are published in the English language;
- CAVE systems or XR headsets are used in applications for the cultural heritage domain;
- Studies have been indexed by Scopus.

The exclusion criteria are highlighted in the second list below:

- Review articles, theses, web pages, or oral presentations;
- Non-English papers;
- Applications for cultural heritage domain not employing XR technology;
- XR-based applications for cultural heritage domain employing non-immersive 2D handheld devices, such as smartphones, tablets, or desktops;
- Articles without available full text.

After duplication removal, titles and abstracts were used as a first step in the eligibility screening process for articles, followed by a full-text analysis. The studies were then divided into subgroups based on the topic matter to which they were applied. Fig. 1 schematizes the selection procedure.

3.3. Quality assessment

After paper selection, a quality assessment process has been conducted on the selected works to determine their consistency. Different factors were considered in order to assess quality, referring to criteria selected by Kitchenham et al. [14] and adapted for the evaluation of studies for review purposes. Two academics

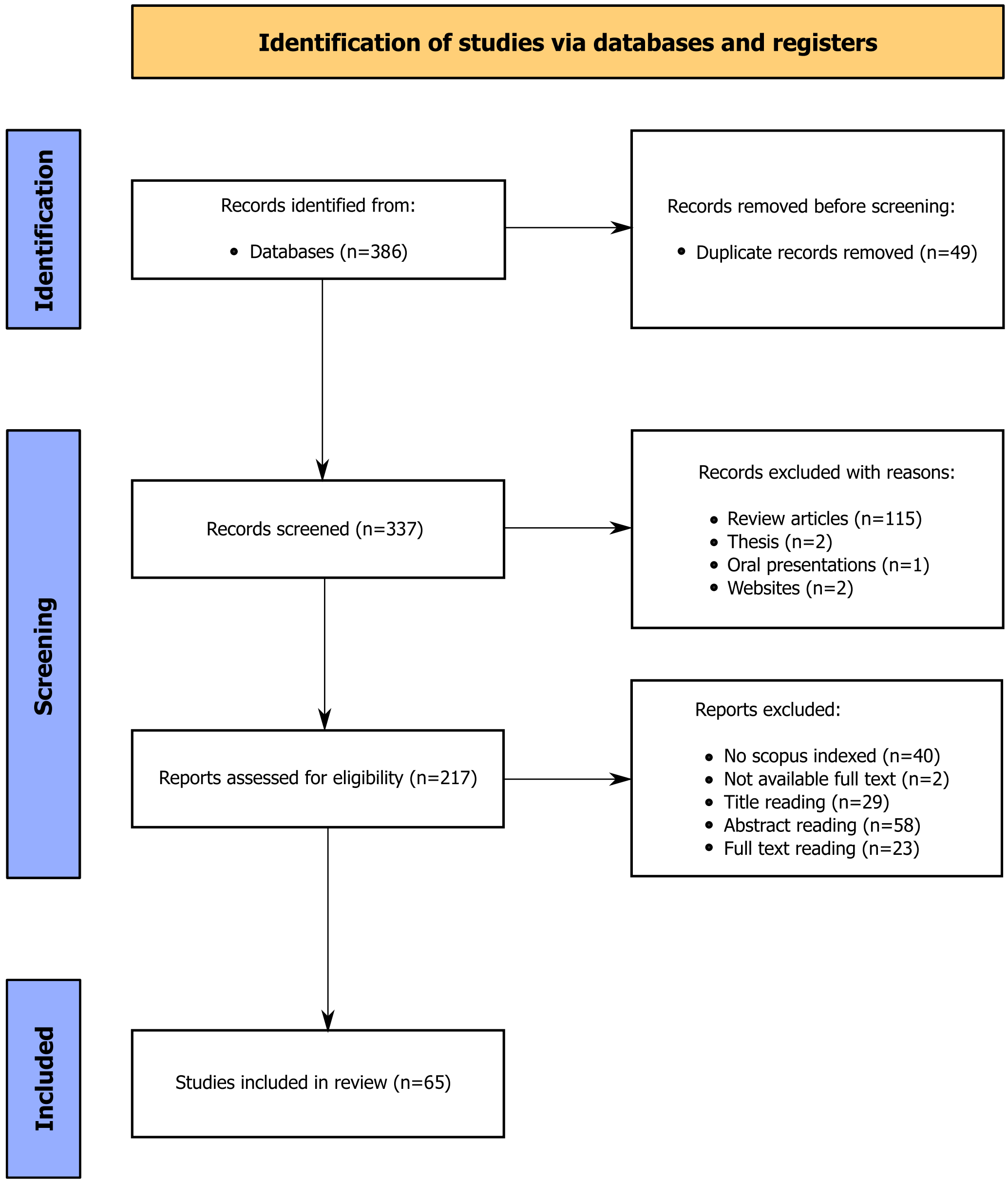


Fig. 1. Flowchart featuring the paper screening process. The flowchart is prepared in accordance with the PRISMA template.

worked separately on the evaluation grading each paper on a scale of 1 to 3 (low, moderate, and high). A third researcher repeated the procedure only when the results differed, independently deciding which score to assign. The cumulative weight of evidence (woe) [15] has been calculated for every publication by assigning scores to each of the following questions, with a scale ranging from 5 to 15, where 5 corresponds to low, and 15 to high:

1. Are the design and structure of the research appropriate?
2. Is the research methodology transparently reported?
3. Are the findings consistent with data and analysis?
4. Is the interpretation of results adequately supported by data?
5. Is the research design allowing us to find relevant information to answer the research questions?

Fig. 2 shows the histogram of the frequency distribution of woe. As seen in the diagram, the majority of the selected papers received high scores, and the average position was found to be 10.70. It was expected to be high, as we considered studies that were published in Scopus-indexed peer-reviewed scientific journals and conferences.

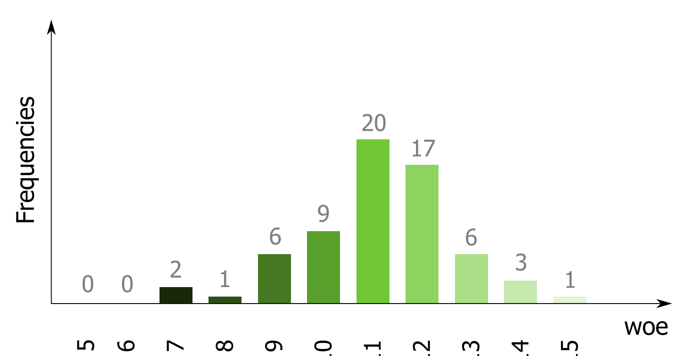
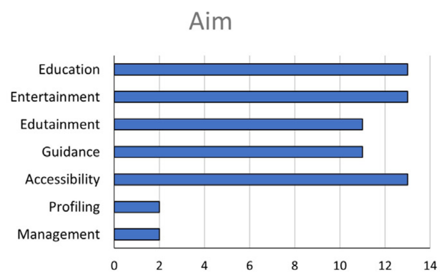
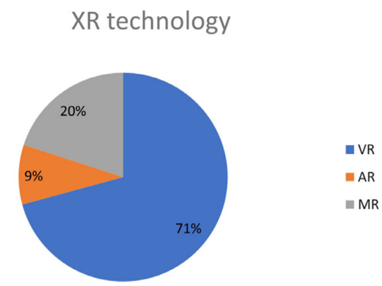


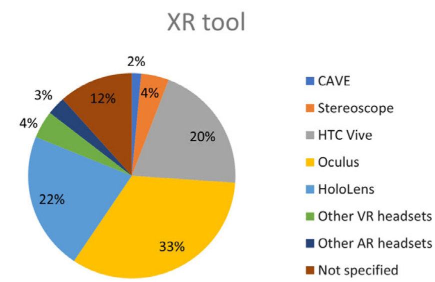
Fig. 2. Quality assessment. Frequency distribution histogram of woe assigned to each paper.



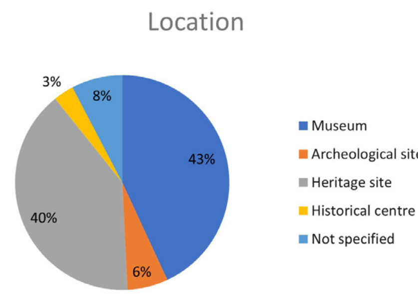
(a) *Aim of the study*



(b) *XR technology involved*



(c) *XR visualization tool used*



(d) *Intended location*

Fig. 3. Diagrams resume statistical analysis performed on results obtained from paper selections. (a) shows the occurrences of the analyzed studies grouped by aim. (b) highlights the involved XR technologies and (c) the adopted devices. (d) displays the locations where the solutions were intended to be employed.

4. Results

This review considered sixty-five studies to be significant, and the collected data were analyzed in Microsoft Excel. Table 1 describes the qualitative characteristics of the included studies, specifically the author, the year of publication, the XR technology involved, the main purpose and the type of study, the type of headset, smart glass or HMD used as a visualization tool, the location where the developed products are intended to be used.

The diagrams in Fig. 3 summarize the results from Table 1.

According to the main purpose of the developed application, the vast majority of the case studies concern applications intended for education ($n = 13$) and entertainment ($n = 13$) purposes (Fig. 3(a)). This is understandable given the educational nature of cultural venues as well as the growing desire to provide visitors with a complete experience in which the educational process of learning is accompanied by playfulness and enjoyment of the cultural experience. This idea is expressed by the neologism ‘Edutainment’, which emphasizes the importance of incorporating stimulating and entertaining activities into the learning process and has been considered as a stand-alone category ($n = 11$). A large number of studies also concern applications to promote cultural site accessibility ($n = 13$) in terms of architectural barriers removal, making accessible places that are unreachable to most (such as underwater archaeological sites), or reconstructing cultural sites that have been lost or destroyed. Many studies have also explored the possibility of using HMDs for the development of tour guide systems to aid or replace human museum guides ($n = 11$). Only fewer studies were found to deal with visitor profiling ($n = 2$) and heritage site management ($n = 2$).

As the graph in Fig. 3(b) shows, nearly 75% of the studies examined deal with VR applications ($n = 46$), while only slightly more than 25% deal with AR/MR applications ($n = 6, n = 13$). As a result, the type of headset used reflects this division: as seen in Fig. 3(c) the Oculus VR headset, in its various models, is the most commonly used in cultural heritage applications ($n = 23$). HoloLens, both 1 and 2, is the second most popular HMD ($n = 15$). This is explained by the fact that the best-selling visors are Oculus and HoloLens, whose technical characteristics make them particularly suitable for these purposes. Only three studies used a stereoscope, and only one study reported the use of a CAVE system for cultural heritage applications.

The majority of the environments for which the applications are intended are indoor environments ($n = 58$), particularly museums ($n = 28$) (Fig. 3(d)). In fact, museums have used these technologies to enhance their customers’ visiting experiences by offering personalized visits with digital content created specifically for the historical and cultural context of their resources. Only a small percentage of applications, such as old city center exploration ($n = 2$), and archaeological site excavations discovery ($n = 5$), are intended for outdoor use. These applications are more difficult to develop because the visitor’s experience is strongly related to the outdoor environmental conditions, such as the delimitation of the area reserved for the virtual experience and the management of obstacles.

Based on this division, the studies were grouped as follows: studies intended for education purposes (Section 4.1), studies intended for entertainment purposes (Section 4.2), studies intended for both education and entertainment (edutainment) purposes (Section 4.3), touristic guidance system applications (Section 4.4), applications intended to enhance accessibility to heritage sites (Section 4.5), implementation of visitor profiling studies (Section 4.6) and studies that present heritage site management implications (Section 4.7).

4.1. Education

Involving the public in cultural tasks is of utmost importance for museum institutions. An effective tool that allows them to achieve this goal while reaching out to the public efficiently consists of immersive XR technologies. HMDs allow to display the en-

Table 1
Analyzed studies presenting XR headset-based solutions in the cultural heritage domain.

Authors	Publication year	XR Technology	Purpose	Type of study	Location	Visualization tool
Aiello et al. [16]	2019	VR	Edutainment	Application	Museum	Oculus Rift
Anastasovitis et al. [17]	2018	VR	Edutainment	Application	Museum	Oculus Rift
Argyriou et al. [18]	2020	VR	Guidance	Design & Development	Historical centre	Oculus Rift
Balbi et al. [19]	2021	VR	Accessibility	Design & Development	Not specified	Oculus Rift
Banfi et al. [20]	2021	VR	Education	Application	Heritage site	Oculus Rift
Baradaran et al. [21]	2022	VR	Edutainment	Evaluation	Museum	HTC Vive
Barbera et al. [22]	2022	VR	Accessibility	Application	Heritage site	Stereoscope + CAVE system + Oculus Quest 2
Barreau et al. [23]	2020	VR	Education	Application	Archaeological site	HTC Vive
Bekele et al. [24]	2019	MR	Entertainment	Design & Development	Not specified	HoloLens 1
Bekele et al. [25]	2021	MR	Entertainment	Design & Development	Heritage site	HoloLens
Bolognesi et al. [26]	2020	VR	Edutainment	Design & Development	Museum	Oculus Rift S
Bozzelli et al. [27]	2019	VR	Edutainment	Application	Museum	HTC Vive
Bruno et al. [28]	2018	VR	Accessibility	Application	Heritage site	HTC Vive
Cai et al. [29]	2018	VR	Education	Evaluation	Heritage site	HTC Vive
Choromaáski et al. [30]	2019	VR	Education	Application	Museum	Oculus Rift
Comes et al. [31]	2020	VR	Education	Application	Archaeological site	HTC Vive
Comes et al. [32]	2022	VR + AR	Education	Design & Development	Archaeological site	Oculus Meta Quest + HoloLens 2
De Paolis et al. [33]	2022	VR	Accessibility	Application	Heritage site	Oculus Quest 2
Debailleux et al. [34]	2018	VR	Guidance	Application	Historical centre	Oculus Rift
Debandi et al. [35]	2018	MR	Guidance	Application	Heritage site	HoloLens
Drossis et al. [36]	2018	VR	Education	Application	Heritage site	Oculus Rift
Duer et al. [37]	2020	VR	Accessibility	Application	Museum	Not specified
Egea-Vivancos et al. [38]	2020	VR	Edutainment	Evaluation	Not specified	Oculus Rift + HTC Vive
Errichiello et al. [39]	2018	VR	Profilation	Application	Heritage site	Samsung Oculus Gear VR
Falconer et al. [40]	2020	VR	Entertainment	Application	Heritage site	Oculus Rift
Galdieri et al. [41]	2019	VR	Entertainment	Evaluation	Not specified	Not specified
Geronikolakis et al. [42]	2020	MR	Edutainment	Design & Development	Heritage site	Not specified
Hajirasouli et al. [43]	2021	VR	Accessibility	Evaluation	Heritage site	Oculus
Häkkilä et al. [44]	2019	VR	Accessibility	Application	Museum	Oculus Rift
Hammady et al. [45]	2020	MR	Edutainment	Design & Development	Museum	HoloLens
Hammady et al. [46]	2020	MR	Guidance	Application	Museum	HoloLens
Hammady et al. [47]	2019	MR	Guidance	Design & Development	Museum	HoloLens
Hammady et al. [48]	2021	MR	Guidance	Evaluation	Museum	HoloLens
Horäkovä et al. [49]	2019	VR	Entertainment	Application	Museum	HTC Vive
Kaghat et al. [50]	2020	AR	Guidance	Application	Museum	Not specified
Kersten et al. [51]	2018	VR	Guidance	Application	Museum	HTC Vive
Krzywinska et al. [52]	2020	MR	Edutainment	Design & Development	Museum	HoloLens
Kusajima et al. [53]	2018	VR	Entertainment	Application	Museum	Not specified
Litvak et al. [54]	2020	AR	Guidance	Application	Museum	Everysight Raptor cycling
Loaiza et al. [55]	2020	VR	Education	Application	Museum	HTC Vive
Masciotta et al. [56]	2019	MR	Management	Design & Development	Not specified	HoloLens
McCarthy et al. [57]	2019	VR	Accessibility	Application	Heritage site	Not specified
Obeidy et al. [58]	2018	AR	Guidance	Application	Heritage site	Google Glass
Parker et al. [59]	2019	VR	Entertainment	Evaluation	Museum	Not specified
Pehlivanides et al. [60]	2020	VR	Accessibility	Application	Heritage site	Oculus Rift S
Pérez et al. [61]	2020	VR	Accessibility	Application	Heritage site	Lenovo headset
Petrelli et al. [62]	2019	VR	Entertainment	Evaluation	Heritage site	Stereoscope
Puig et al. [3]	2020	VR	Education	Evaluation	Museum	HTC Vive
Ragusa et al. [63]	2019	AR	Profilation	Design & Development	Heritage site	HoloLens
Schofield et al. [64]	2018	VR	Education	Application	Museum	Stereoscope
Secci et al. [65]	2019	VR	Accessibility	Application	Heritage site	Oculus Rift
Selmanović et al. [66]	2020	VR	Edutainment	Evaluation	Heritage site	Not specified
Settembrini et al. [67]	2018	VR	Education	Application	Heritage site	Oculus DK2
Sylaiou et al. [68]	2019	VR	Guidance	Evaluation	Museum	Oculus Rift
Tennent et al. [69]	2020	VR	Entertainment	Application	Museum	HTC Vive
Teruggi et al. [70]	2022	MR	Management	Application	Heritage site	HoloLens 2

(continued on next page)

Table 1 (*continued*)

Authors	Publication year	XR Technology	Purpose	Type of study	Location	Visualization tool
tom Dieck et al. [71]	2019	VR	Entertainment	Evaluation	Museum	Samsung Oculus Gear VR
Trichopoulos et al. [72]	2022	AR	Accessibility	Application	Museum	HoloLens 2
Trindade et al. [73]	2018	VR	Edutainment	Evaluation	Heritage site	HTC Vive
Trindade et al. [74]	2022	VR	Edutainment	Evaluation	Heritage site	HTC Vive
Trizio et al. [75]	2019	VR	Accessibility	Design & Development	Heritage site	Oculus Rift
Vlizos et al. [76]	2021	MR	Education	Application	Archaeological site	HoloLens 2
Yoo et al. [77]	2019	VR	Entertainment	Application	Museum	Oculus
Zerman et al. [78]	2020	MR	Education	Evaluation	Museum	HoloLens
Zhang et al. [79]	2021	VR	Edutainment	Application	Heritage site	Oculus

vironment in which an artwork was made or the space in which it is typically shown, so that the visitors may have a stronger connection to the artwork itself as a result of having a deeper understanding of the meaning and context of the piece. This can enhance the learning process, providing useful and engaging information to the visitor while observing each work.

Among the contributions describing the creation of immersive educational material, the visualization of 3D data and virtual models using a headset is extremely important in sharing and learning about the history of a place. The integration of XR in 3D reconstruction is a very powerful learning tool. The digitization of an existing monument [20,30], or the reconstruction of a poorly preserved structure [31], as well as the possibility of interaction with virtual spaces and objects contributes to the promotion of cultural heritage and improves knowledge of these sites by provoking critical feedback and increased awareness. However, the development of these applications is often hampered by misinterpretations and archaeological misunderstandings, which need to be addressed carefully [23]. Furthermore, full-quality data and measurements cannot be used directly for visualization due to the actual limitations of game engines and hardware processing power, introducing the need for additional data preparation processes to achieve a good compromise between easy-to-visualize low polygon 3D models and optimal reconstruction accuracy.

XR technology can assist cultural heritage institutions and museums in preserving and presenting their collection in novel and original ways. With XR, visitors can interact with historical artifacts, explore virtual environments, and engage with cultural content in ways that were previously impossible. For instance, it offers the possibility to manipulate artifacts up close, eliminating the physical distance between the exposed objects and the visitor. Some examples are the works of Drossis et al. [36] and Settembrini et al. [67], whose virtual environments allow people to interact with virtual reproductions of cultural artifacts and historical objects, and obtain information through gestural interactions and eye and head movements. Leap Motion was employed in both cases to track and animate virtual hands, even though tracking instabilities still occur due to occlusions between fingers or palms.

The public can hardly develop a complete understanding of society only by artifacts or archaeological remains. Thus, providing the context can result of upmost importance not only to improve the visitors' experience in terms of attractiveness but also to enhance the comprehension of the works' intrinsic meaning. To this aim, Puig et al. [3] simulated the Neolithic settlement of La Draga using a VR headset. The experience includes a series of interactive and non-interactive activities, such as observing ancient artifacts, experimenting with the technique of stone carving, watching videos about the population, customs, and agricultural activities, and a game to make participants aware of the learning about Neolithic society during the exhibition.

Cai et al. [29] also used a VR headset to virtually simulate the daily life of the Ningbonese population in a 3D reconstruction of characteristic dwellings. Their study showed how VR reconstructions of cultural heritage can trigger memories and a sense of familiarity in individuals who are familiar with the objects and scenes. A similar educational approach was also adopted by Vlizos et al. [76], in which Microsoft HoloLens has been used to simulate an archaeological excavation of a trench layer by layer, providing, for each step of the process, the information needed to understand its dynamics.

Another advantageous feature of these new technologies consists in the opportunity of creating novel virtual exhibitions by gathering in the same place artworks located in different museum spaces [55], or temporarily not on public display due to restoration interventions [32] (Fig. 4).

When used in an educational setting, XR technologies allow to speed up the learning process by using a novel method of knowledge transmission that allows the learning experience to be tailored to a more modern audience. Future research should focus on the management of complex information, such as intangible resources. For these elements of interest, the contribution provided by XR technologies could be even more impactful, since it is difficult to convey with other traditional approaches, resulting in a less significant experience.

4.2. Entertainment

XR technologies are an opportunity for museums because they provide the possibility to offer many different and immersive experiences using the same headset that is adaptable to different environments. The use of headsets in cultural contexts gives visitors the opportunity to obtain fully interactive and engaging interpretations of stories, works of art, and archaeological sites.

Bekele et al. [25] proposed a cloud-based HoloLens MR application that uses multi-user collaborative interaction to enhance the engaging aspect of the learning process. The type of interaction is map-based, in which a walkable MR Map is used as an interactive interface to manipulate 3D models of artifacts in the virtual environment [24]. The authors mentioned some technical challenges regarding the computational resources required for MR application development with the HoloLens devices; these include the use of constantly updating development frameworks, such as MRTK, which causes incompatibility issues between devices and applications versions, or the use of additional cloud-based storage to prevent the degradation of device performance due to the loading of all content at runtime.

Falconer et al. [40] developed a VR simulation of the Neolithic Avebury Stone Circle and Henge complex how it may have looked in 2300 BC. The multi-user experience was fully immersive, as visitors received visual and auditory cues via 3D headsets and haptic devices. Two adult avatars of a Neolithic man and woman accompanied visitors as they explored the virtual space. The engagement aspect was enhanced by the possibility of seeing other participants

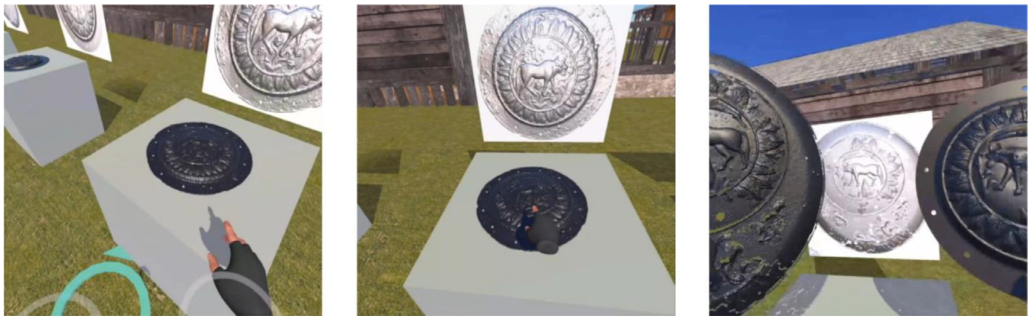


Fig. 4. Illustration of a VR application with education purpose. Snapshots of the VR applications while the user is interacting with 3D scanned and 3D reconstructed artifacts. Picture taken from Comes et al. [32].

simultaneously present in the simulation and communicating with them through speech or text.

Horäkovä et al. [49] reproduced in VR the entire Computer Graphics, one of the first computer art exhibitions, staged in Czechoslovakia in 1968, modeling the movement from the visitor's perspective, allowing a virtual tour of the exhibition and the possibility of observing the art objects up close or from distance. In a very similar way, Tennent et al. [69] replicated the first photographic exhibition in the world in a room-scaled application based on VR, Tresholds. Room-scaled VR allows visitors to physically walk in the virtual environment: in particular, the real world matches the virtual environment along the transverse direction, while the longitudinal direction of the virtual environment is much greater so that only a portion of the virtual environment is physically walkable. The shapes of the objects in the virtual room exactly match the real ones, so by juxtaposing the virtual objects against the real ones, it is also possible to provide tactile feedback to the visitor. Nevertheless, matching real and virtual objects should be done as accurately as possible, yet the alignment between physical and digital resources is inevitably susceptible to human error, as human calibration is required even in automated systems. Careful design of spaces, both physical and digital, is necessary to properly delineate their boundaries and characteristics. Yoo et al. [77] wanted to reproduce the same artwork in VR, in different and unexpected environments for an art museum, and measure the user's reaction to the different settings. Each environment has its own mood and feeling, and this was a perfect collateral element for an art museum since art should arouse emotions. Instead, Kusajima et al. [53] proposed that audiences use their bodies to reproduce, through VR, 'Yose-e' works, a type of Japanese ukiyo-e paintings that creates the illusion of a single large person or object composed of many people or objects assembled together. However, the dimension of the space provided for conducting the experience placed some limitations on the space available for necessary hardware equipment, thus limiting the experience to a single user at a time.

Digital environments are employed to engage visitors actively and emotionally, offering the public the opportunity to integrate the knowledge and experiences offered by the cultural venue with their own. The use of XR technologies can be a tool to encourage interaction between users during the cultural experience and stimulate the sharing of the experience itself. Given the diversity of the target audience, XR applications should be designed with appropriate levels of difficulty; this way, people from different cultural backgrounds can carry out the experience in an engaging environment even in the absence of explicit instructions.

4.3. Edutainment

Edutainment is a form of educational entertainment, i.e., aimed at promoting learning in a playful and entertaining context. The introduction of XR technologies in cultural frameworks has fostered the development of this concept, and in this type of application, it has expressed its maximum communicative potential, bringing a traditionally distant category of users closer to cultural environments. In this context, Aiello et al. [16] developed a complete workflow involving 3D modeling, attractive storytelling, and experiencing VR through an Oculus Rift device. Storytelling is core in an edutainment application since attractiveness directly impacts the user's engagement and, consequently, the user's learning ability. The developed prototype, Timeless Museum, uses VR to create an emotional learning experience in which masterpieces from all times, although belonging to different cultural institutions, are brought together in the same place (Fig. 5).

The idea of edutainment is the foundation of serious games, which are games aiming to educate while also entertaining. There are numerous examples of VR-based serious games in the literature. Anastasiovitis et al. [17] proposed three serious games for Oculus as part of the Digiart European Union-funded project: the Scladina cave in Belgium is the subject of the first case study; the second case study replicates a digital anthropological museum; the Palace of Aigai in Greece serves as the third case study's public interface. Bolognesi et al. [26] developed a serious game to promote the Milanese museum Studio Museo Achille Castiglioni and introduce the public to the works and genius of the master Castiglioni. Bozzelli et al. [27] proposed, in the context of the ArkaeVision project, ArkaeVision Archeo, an HMD VR-based experience that integrates the 3D reconstruction of the archaeological site of the temple of Hera in Paestum; the actual practicability of this system in terms of guides and operators, however, needs to be further investigated, since the demo considered in this study was considered too short by the participants and there were some issues related to motion and locomotion sickness. Egea-Vivancos et al. [38] developed a cooperative historical video game for learning about the culture and archaeological contents of Roman theatres. Zhang et al. [79] created a VR game for promoting the art and culture of Dunhuang grotto murals. Selmanović et al. [66] released an educational experience and quiz sessions on intangible bridge diving traditions that, if correctly answered, gave access to a virtual bridge diving at Stari Most (Mostar Bosnia). Also, MR-based serious games have been released: Krzywinska et al. [52] developed a co-designed social escape room experience to simulate a World War II telegraph exercise using Microsoft HoloLens, while Geronikolakis et al. [42] simulated the entire construction of Knossos and restoration of Sponza, creating an MR-based serious game to learn about the buildings from within the archaeological site.

Since the learning ability depends on users' collaborative participation in the learning process, the interactive features of XR applications would be able to facilitate active learning increasing users' attention. Nonetheless, clear guidelines need to be developed on which features of an XR environment a designer should focus on to

Fig. 5. Example of VR application with edutainment purpose. Snapshot of a scene of the VR application presenting a “dystopian dimension”. Figure is taken from Aiello et al. [16].

increase user engagement and improve the learning process during the experience.

4.4. Touristic guidance systems

In recent years, XR technologies have been gaining ground in the field of cultural heritage as replacement or assistance systems for the role of human guides within museums and archaeological sites. Their ability to provide additional audio-visual information to visitors makes them extremely suitable for this role, allowing customers to tour independently, without any temporal and/or spatial constraints, boosting the time people spent in museums and making the overall experience more engaging.

In this context, Debandi et al. [35] developed a smart guide for outdoor environments that relies on an application for HoloLens. Through a client-server application, HoloLens sends a continuous stream of images of what the visitor is looking at. A remote visual search engine processes the received images by comparing them with a database and sends a feedback signal if the observed object is recognized. In this way, the visitor is provided with different augmented virtual content (such as 3D reproductions, images, and videos, textual content, etc.) depending on what is observed. Nevertheless, images recognition and tracking with Vuforia were discovered to be unreliable since both recognition and tracking can be hampered by any change in light or movement of each object or user compared to the images uploaded to the database.

A similar approach for outdoor guidance systems was also used by Litvak et al. [54]. Places and object recognition, in this case, were realized by employing a localization and orientation system in which the coordinates of POIs are recorded. In the proximity of a POI (5–6 m), the system announces its name and then provides all the available information to the visitor. A further application of an outdoor tourist guidance system is TouristicAR, described in the work of Obeidy et al. [58], which allows visitors to explore Malaysia’s UNESCO cultural heritage by wearing a Google Glass equipped with an internet connection, in which Google Places API can work (Fig. 6).

A different system, Sound Augmented Reality Interface for visiting Museum (SARIM), was proposed by Kaghat et al. [50]. The AR-based audio system is adaptive and provides cues, comments, and background sound in the form of binaural audio, depending on the position and behavior of the visitor inside the museum (focus, stop, movement), and proximity to artifacts. In this way, each visitor’s path within the museum is unique, and the visit experience is customized based on each behavior. Similarly, Debailleux et al. [34] organized a VR tour specifically for children with Oculus Rift in the main square of the city of Mons (Belgium) to explore the buildings around the square. The VR tour is guided by audio descriptions, activated when the user is in the vicinity of a particular building. The evaluation results indicate that although children also acquire most tourist information through audio descriptions, in the learning phase visual knowledge of buildings and their architecture is more significant than historical details.

Kersten et al. [51] proposed a virtual reconstruction of the wooden model of the Temple of Solomon, which can be found in the Hamburg Museum. The virtual 3D model was uploaded into a game engine to develop a VR application for the HTC Vive headset, in which the model could be scaled to the size of its real wooden counterpart, or the actual size of the building so that it could be visited virtually. The application offered the opportunity to organize guided virtual tours thanks to the multi-user functionality, whereby several users could communicate with each other during the virtual tour using a microphone.

The MuseumEye application developed by Hammady et al. [46] introduces the virtual avatar of Pharaoh Tutankhamun during a guided tour of the Egyptian museum in Cairo for approximately 30–40 min. The virtual guide accompanies the visitor, equipped with HoloLens, along a tour of the Tutankhamun chamber and stopped at the predetermined stations. A holographic user interface, specifically designed for the narrow field of view of HoloLens, allows the guest to engage with the virtual replicas of items in the museum and observe them up close [47]. The potential role of the application was evaluated in Hammady et al. [48] and proved that the MR-based guidance system can stimulate the visitor to use it in the future. On the other hand, those evaluations also revealed inherent issues related to the use of HoloLens in overcrowded environments. Specifically, the complexity of congested corridors, rooms, and visiting paths is difficult for HoloLens to handle without interrupting the application workflow.

Argyriou et al. [18] also employed two virtual actors to develop a virtual tour in the historical city center of the Greek city of Rethymno (Fig. 7). One was in charge of narration, providing information about the initial scene, and the other was used to direct the visitor to a particular POI, providing historical information, and motivating the user to continue the tour. The types of avatars as tour guides in a museum were evaluated by Sylaiou et al. [68] in a work in which three different human avatars (a museum curator, a security guard, and a museum visitor) narrated the same story about an artifact with different accents and characteristics depending on the character. The evaluation showed that the emotions provoked in visitors by the narratives of the different avatars are different; it is essential that museum curators appropriately design the type of virtual guides they want to employ, depending on the emotions they want to arouse in their visitors.

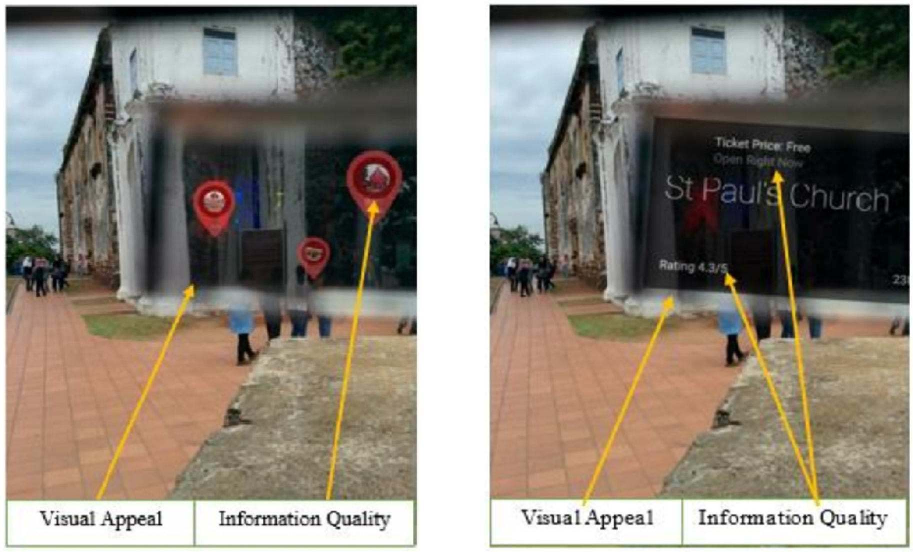


Fig. 6. Example of XR application with touristic guidance purpose. Snapshot of the UI implementation of the TouristicAR app. Figure taken from Obeidy et al. [58].

Fig. 7. Example of CH application with touristic guidance purpose. Rethymno 360° immersive video virtual tour scenes and design elements. Figure taken from Argyriou et al. [18].

The provisioning of objective and reliable information is an essential need for the use of XR systems to supplement or replace human guides. Extra caution must be taken when planning cultural itineraries and defining factual historical reconstructions in order to prevent misinterpretation of information, which can result in misinformation and have impacts both on visitor learning and on the credibility of the cultural institution.

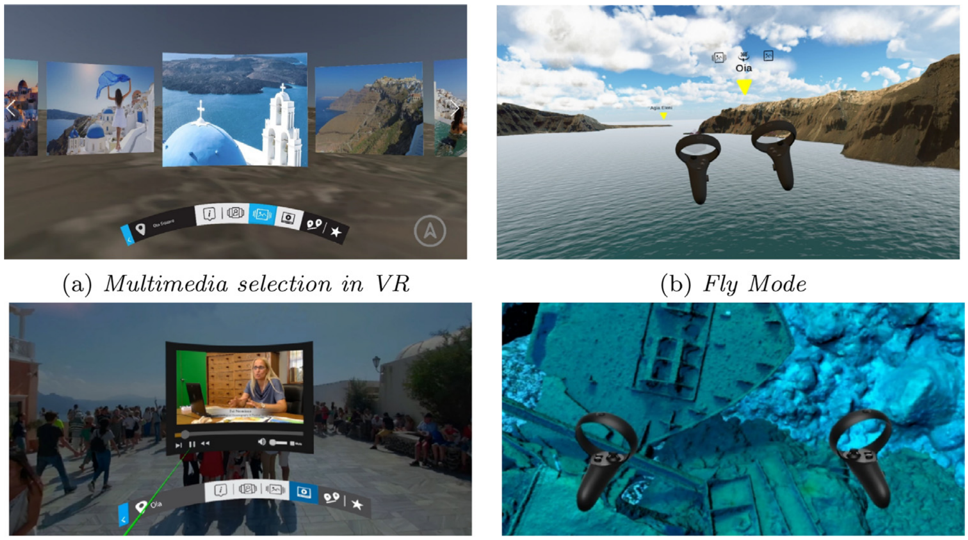
4.5. Accessibility

The term “accessibility” is used in the literature to indicate the ability to make a cultural heritage content or service available to the public without distinction, including people with disabilities, who require special assistive technologies. However, it is also used to indicate the possibility of easy access to a place, dependent on factors such as the morphology of the territory, the care and cleaning of the surrounding environment, and the conservation status and preservation policies of heritage sites.

Regarding applications aimed at improving the accessibility of cultural heritage content to users with disabilities, an example is given by Balbi et al. [19]. The design process of a VR scenario for the fruition of cultural content also involved users with motor disabilities, in order to identify all the basic requirements for this type of application, regarding different types of disabilities. In this way, a VR solution for cultural heritage was developed according to the principle of User-Centered Design (UCD), considering the expectations and needs of users with disabilities from the beginning of the design process, and not only in the last stages of testing. Another example concerns the development of a VR application for a virtual visit to the archaeological site of Cancho Roano, one of the most important monuments of protohistoric Spain [61]. The virtual tour allows wheelchair users to be able to virtually visit the monument, with the advantage of avoiding architectural barriers that often slow down or prevent access. Specifically, visitors have to wear a VR headset integrated with a motion simulator with a haptic interface. This allowed wheelchair users to be able to experience real sensations, such as the roughness of the ground and the inclination of surfaces under their wheelchair, enhancing the perceived realism of the experience.

Trichopoulos et al. [72] presented the Cultural Heritage Augmented and Tangible Storytelling (CHATS) project, an AR-based digital storytelling system without the use of images, in order to improve the experience of visually impaired visitors in the heritage site. CHATS involves the use of a tangible interface of a work of art (e.g., a 3D printed representation of the characters in a painting). The physical manipulation of the interface can activate, depending on the user’s visual angle with respect to the physical artifact, digital storytelling composed of binaural audio and augmented content provided to the user through a smart glass. In doing so, they exploit HMD capabilities to offer a fun and educational way to browse cultural content.

The VirtualDiver project proposed by Pehlivanides et al. [60] is one of the examples where AR and VR have been used to create an immersive platform to allow visitors to discover the underwater heritage in the Greek sea and so increase tourism in this area. A particular case study was realized for the world-famous island of Santorini (Fig. 8(a)). The VR experience allows the visitor to explore the island from virtual reconstructions of the real environments by simulating a flight from above (Fig. 8(b)), a walk through the city center of Oia along a pre-determined route (Fig. 8(c)), or an underwater diving session in the volcanic crater where the island is located, surrounded by the characteristic flora and fauna (Fig. 8(d)). A VR application developed as part of the iMARECULTURE project is an example of the use of HMDs to bring the intrinsically inac-



(a) *Multimedia selection in VR* (b) *Fly Mode*

(c) *Walk Mode* (d) *Diver Mode*

Fig. 8. Example of VR application to enhance heritage site accessibility. Pictures taken from Pehlivanides et al. [60].

cessible underwater cultural heritage into the digital reach of the general public [28]. People enrolled in marine and archaeology will learn the fundamentals of “site formation,” “surveying,” and “excavation” through the three components of a serious game developed for HTC Vive. The search and discovery component assessed two maritime archaeology techniques for finding artifacts [80], the second one focuses on documenting an underwater site by using a VR camera to take images that will later be used for photogrammetric analysis [81], while the third one emulates the process of excavation of the wreck by taking sand out of the seabed [82].

The inaccessibility of underwater habitats is frequently caused by both the environment itself and, in some circumstances, restrictions deriving from the preservation and protection of underwater cultural treasures. A case is the shipwreck of the Mercury, which sank in 1822 during the Battle of Grado. After the discovery, excavations were stopped due to economic reasons and protection and conservation of the archaeological site, so that now the entire location of the shipwreck is completely unreachable because it is submerged by sand and the seabed. The VR experience proposed by Secci et al. [65] allows the visitor to simulate a realistic immersion in the shipwreck site using an Oculus Rift VR headset, starting from the water surface to full immersion on the seabed, being able to visualize the wreckage thanks to photogrammetric reconstructions as found in the archaeological excavations. Another example is the work of McCarthy et al. [57] who replicated a diving experience for non-divers to discover Iceland’s oldest shipwreck, the Melckmeyt, which sank in 1659. The 2.5-D VR experience includes a 360-degree panoramic animated video viewable through a Samsung Gear VR headset, in which the relief of the wreck is replaced with a speculative reproduction of the ship as it could have seemed immediately after the sinking, allowing visitors to truly perceive the shipwreck as part of a large, now disappeared ship.

A similar approach has been used in the valorization policies of isolated, particularly vulnerable archaeological sites and heritage places, which are considered to be at risk due to the conditions in which they are preserved or the dangerousness of their surroundings [22,33,37,43,44,75].

VR headsets made it possible to create frameworks in which virtual reconstructions of damaged heritage sites could be displayed, and the environment and atmosphere simulated as accurately as possible, without affecting the realism of the entire experience [44]. The high degree of immersivity that these tools provide makes it possible to involve a larger number of people and create a high degree of participation even for archaeological sites in which interest has been lost, or which cannot be restored, providing the continuation of tourism in complete safety [22]. However, the quality of the user interface, or rather the simplicity of handling the controllers, as well as easy management of the navigation system of the virtual world are all factors that must be considered while developing these apps. In order to reach an audience as wider as possible, these systems should be simple to use for all users with little or no acquaintance with these technologies, such as children or the elderly, even though it is generally acknowledged that younger adults are more interested in using them [44].

4.6. Visitor profiling

AR and VR HMD-based applications have become popular in museums and cultural sites also as visitor profiling tools. These devices can provide useful insights into the perceptions of guests of a cultural site and can collect important data with the aim of profiling tourists. This would allow cultural sites to provide their visitors with diversified and customized content, suggest a preferred visit route, and increase the enjoyment of cultural content, enhancing the overall experience.

Ragusa et al. [63] developed a system based on a HoloLens application that can assist a tourist during a visit. The HMD provides the visitor with additional cultural content through holograms, and, in addition, is capable of keeping track of important data, such as the user’s location within the museum, the artifacts that have already been viewed, and the time spent in front of each work. The study of the data collected from each visitor can provide important information on visitors’ behavior and preferences, assess which locations are preferred by users, and organize more appropriate guidance paths. A further function might involve tracking which cultural artifacts are mostly observed by tourists, providing additional insights into visitors’ preferences. Errichiello et al. [39] analyzed data collected from 287 interviews to assess the level of attraction of the “San Teodoro Experience” project and its VR-based experience prior to its inauguration and opening. A cluster analysis was performed in order to profile the visitors and

Fig. 9. Example of MR application for cultural heritage sites management. The pictures refer to a project regarding Bologna porticoes taken from Teruggi et al. [70].

to verify whether socio-demographic differences and emotional responses modified the perception of the VR experience as a whole. The three clusters of visitors obtained showed differences in the perception of VR, with a more positive emotional response for the VR-enthusiasts cluster.

These findings demonstrate how it is possible to provide visitors with cultural experiences tailored to their features and preferences, and enhance their emotional reactions through VR tools. Nevertheless, the main drawback of these studies is the poor composition and small size of the samples used to collect data and perform statistical analysis. Indeed, these studies must be expanded to include additional museums and heritage sites in order to cross-validate the findings to enable more extensive generalizations.

4.7. Cultural heritage site management

Preservation, monitoring, and preventive maintenance of cultural and historical heritage require a complicated decision-making process and the personal involvement of owners and curators. Of paramount importance is the process of constantly updating the documentation of cultural heritage so that it is easily accessible and consultable by everyone.

The HeritageCare project, described in the study by Masciotta et al. [56], presents a MR-based methodology for the creation of a protocol for the inspection of cultural heritage and the digitization of documentation and its related information. Using a HoloLens, inspectors have access to the virtual model of a heritage site, retrieve the corresponding technical information such as data from previous inspections, or update it with new measurements. In addition, the protocol integrates common documentation and classification criteria for condition and risk analysis to provide an objective evaluation of the current state of cultural heritage conservation. Teruggi et al. [70] presented three case studies (the Temple of Neptune in Paestum, the Milan Cathedral, and Bologna's porticoes) for the application of a framework for the management of large 3D point cloud data (Fig. 9). The use of an HMD device allows the high-resolution visualization of these data in full, or by segmenting entire building blocks or individual architectural elements, and then inspecting them in close detail. This application has implications both in the field of tourist guides, e.g., by positioning information hotspots in crucial locations and in the context of maintenance interventions.

Clear and consistent documentation and monitoring procedures provide the basis for the protection of cultural heritage. Indeed, major problems with classification, integration, administration, and access may arise as a result of the significant quantity of heterogeneous information and data collected for each item. These technologies can therefore have a huge impact on the categorisation, analysis, and traceability of the high volume of data from different inspection and diagnostic approaches. These aspects will be discussed in the next Section.

5. Discussion

The concept of "cultural heritage site" has evolved significantly over time. Whereas previously cultural sites represented static warehouses to acquire, preserve, conserve, and study artifacts, their mission has now changed. People today consider cultural sites as active learning environments, where the importance of objects is questioned in favor of the importance of information [83]. The entire cultural experience is now designed in a user-centric manner: every aspect of the offered experience and activities must contribute to the visitor's satisfaction and the advancement of the visitor's knowledge.

The use of digital technologies like AR, MR, and VR offers new forms of learning, makes knowledge and works accessible, and allows the visitor to personalize the visit; the development of XR serious games engages new audiences, traditionally far from cultural environments, thanks to the type of interaction and the familiarity of the storytelling, facilitating their learning in an edutainment key using the "learning by doing" paradigm. On the management side, the use of these technologies allows for better analysis, profiling, and management of the general public. The direct consequence of these considerations is the creation of more attractive visitor routes based on guests' preferences.

All these concepts reach their maximum expression in the use of immersive devices, such as AR HMDs, VR headsets, and CAVE systems. These immersive technologies allow a controlled exploration of the environment and the presentation of information with greater depth and breadth. This method of presenting cultural content encourages psychological immersion and a sense of presence, both of which increase engagement and make visitors more prone to knowledge awareness.

Results from Table 1 were statistically analyzed to respond to RQ1, and the results are shown in Fig. 3. Furthermore, our first research question was answered above and discussed in Section 4. Section 5.1 specifically focuses on the advantages of XR headset-based versus handheld XR-based applications in order to answer RQ2, while Sections 5.2 and 5.3 answer RQ3, discussing the issues encountered by authors in the employment of such technologies in the cultural heritage domain both from the designer and the user perspective.

5.1. Advantages and limitations over handheld devices

Handheld devices dominate the broad landscape of XR-based applications for the cultural heritage domain [84]. This is not surprising given that cultural heritage XR applications are mainly based on the "Bring Your Own Device" (BYOD) concept [84,85], which is the policy that allows people to use their personal devices during the cultural experience. Indeed, visitors interact with their own devices more intuitively and familiarly, and some devices may already be optimized to increase accessibility for people with special needs [54]. Therefore, the aim of many cultural sites is to develop solutions with high-quality cultural content in which visitors use their own devices, whose portability is suitable for visiting cultural sites, for instance using their camera to point in a direction while interacting with the touch screen [85]. This is unquestionably advantageous, as, by implementing this policy, cultural institutions avoid providing for a variety of tasks such as renting or purchasing equipment, dedicating storage space for it, keeping the equipment charged and in proper condition, updating content and software, and training and paying staff to assist visitors during experiences and ensure security [84].

However, handheld devices are now regarded as too common and are not considered an attraction for visitors as they now represent the everyday rather than the exceptional. While handheld devices, such as smartphones and tablets are more accessible and less expensive, they can distract visitors from the exhibition to the point of completely disconnecting them from the visit [54]. It can be tiring to hold a smartphone during a visit, and the nature of the interaction, which is confined within the boundaries of the screen, increases the distance between the visitor and the exhibition, resulting in less immersiveness [27,54,62,78]. Furthermore, the accuracy with which they track objects and artifacts is not high [11].

Museum curators and cultural site managers exploit the appealing potential of interactive XR installations and technological devices to attract new users, intrigued by the new multimedia medium. The use of HMDs could be a valuable solution, offering museum visitors a more natural and intuitive means of interaction without the need to carry a device, as well as an uninterrupted experience with no need to switch attention between the screen and the exhibition [86]. Recent research has compared the impressions produced by handheld devices to those produced by more immersive devices, such as headsets and CAVE systems. When compared to a handheld device, headsets provide a more immersive and appealing experience to the user. The combined effect of storytelling and the real surroundings captivated visitors' interest and commitment to further explore that environment, resulting in an educational and valuable tourism experience [27].

In terms of emotion, the use of headsets allows users to feel completely immersed in the virtual scenario and emotionally involved in the story. It is common for evaluations of XR applications for cultural heritage that use headsets to report that almost all users felt an increased sense of presence. The virtual scenes' colors, sounds, and styles aid in recreating the global atmosphere and transporting them to another world. Also, some authors find out that users who wear HMDs dedicate more time to the exploration of their surroundings and in the interaction with the objects they see [46].

The ability of many HMDs to perform eye tracking and head tracking can provide important data on the orientation and position of the head and gaze, and thus confirm the user's direction of interest [47]. This facilitates the development and design of more engaging and personalized visitor experiences and paths, based on what each visitor finds most attractive and interesting.

5.2. Task-specific design and development issues

Although immersive technology based on headsets and HMDs shows considerable potential when applied to cultural heritage applications, some researchers have indicated some important limitations. This Section focuses on design and development perspective.

It is well known that any cultural heritage revitalization project should integrate the reconstruction of historical traces and archaeological remains of the cultural site of interest. The virtual reconstruction and data digitization should preserve the authenticity of the original site or artifact in order to obtain a true and credible model. While artifacts and archaeological remains can provide valuable insights into past societies, they alone cannot provide a complete understanding of the individuals, social, economic, and political contexts that influenced their realization. A multidisciplinary approach integrating humanistic, scientific, and technical knowledge is core to develop a solution capable to provide a comprehensive understanding of a society's history and culture. This highlights the importance of gathering multiple sources of information, including historical records, ethnographic accounts, and oral histories. The undeniable advantage of dealing with a plethora of information has a counterpart; indeed, the heterogeneity of data sources makes it challenging to face all the following steps: image acquisition, view registration, mesh integration and texture generation [87]. To address these challenges, it is essential to have a clear understanding of the depth sensing devices, the data sources, and their limitations, as well as the context and purpose of the application. In this sense, involving experts from different disciplines, such as archaeology, history, and computer science, becomes mandatory to ensure the accuracy and authenticity of virtual models and enhance the user experience.

The reconstruction process should aim to recreate the site or artifact as accurately as possible, while still being mindful of the limitations of available data and the need to make informed assumptions. For those developing immersive applications dedicated to cultural heritage, these issues could be even more challenging, since the reconstruction accuracy determines the realism of the experience and, consequently, its attractiveness and usefulness. Producing high-quality visualizations to impart complex historical knowledge during a cultural heritage visit is highly demanding to such a point that it is often inevitable to find a trade-off between the reconstruction quality and efficient computation [88]. Data availability is a required feature to make virtual objects, environments, or scenarios from the past presented in VR as realistic as possible. When available, the artworks can be 3D scanned or there could be the need of totally or partially reconstruct them thanks to the variety of tools and processes for 3D data collecting [87]. The type and the size of the artwork and the goal of its digitalization determine the best piece of equipment to use in order to obtain the integration of the original data into a single mesh avoiding information loss, unwanted gaps, or artifacts [62]. Moreover, the aesthetic impact of 3D models is enhanced by exact color data, which may also contain crucial information that should be retained, making texture management a key task [23].

There are numerous methods and workflows proposed in the literature regarding the reconstruction of artifacts, buildings, and archaeological remains for their revitalization and enhancement [16,23,32,43,65]. However, in most projects, optimal and detailed models reconstruction still struggles with computing power and limitations of game engines and headsets: the need to obtain detailed meshes produces large polygonal datasets, which are difficult to handle for real-time visualization, actually limiting the complexity and details of the designed virtual environments [30,34,57,61].

Most of the reviewed research requires laborious procedures for tracking and spatial registration between artifacts and the XR system. Registration allows computer-generated objects, such as replicas of 3D models and overlaid information, to be superimposed and placed in a predefined position with respect to the real world. Therefore, especially when talking of MR and AR applications, matching information from the physical world with information from the immersive environment is one of the major problems to be addressed [89]. In fact, since the user interacts with the merged visualization as the final product, researchers should be able to create systems in which actual and augmented objects are virtually indistinguishable from both a geometrical and a photometric perspective [90]. Moreover, information obtained from the external surroundings should assist the user to explore even more deeply the XR environment [3]. Similarly, virtual environment information could assist users in learning about related tourist objects or situations. In connection with this, feedback on the visitor's actions must be provided, as the absence of feedback from the application may cause uncertainty and a lower proclivity to continue using it. Shading and lighting, management of reflections, occlusions, and sizing virtual objects are all issues related to incorrect registration and positioning of augmented objects in the virtual setting, especially when the employed algorithms deal only with color information, instead of also considering the depth data.

Following registration, tracking techniques enable the projected virtual item to hold onto its proper position while gradually responding to human or 3D space movements. Researchers employed a variety of tracking methods depending on the kind of solutions they were developing. When it comes to VR applications, most researchers used an inside-out tracking technique that makes direct use of the camera and sensors in the headset being used [16,21,22,24–26,33,49]. By observing the entire environment, the position of the headset and controllers relative to the real world can be accurately determined through the camera. This allows the user to physically navigate the virtual world and even wander around the room if there is sufficient space (room-scale experiences), interacting directly with virtual objects to further increase the sense of immersion in the VR environment.

The problem worsens, though, when it comes to MR and AR applications. In these applications, knowing the spatiotemporal links between the real and virtual worlds is therefore crucial for enabling the proper integration of virtual models with real-world objects [2]. In order to achieve a proper alignment between the actual world and the virtual information, a fast and precise estimation of the visualization location with respect to real objects must be achieved [91]. Today, many tracking-based systems have been developed and are commercially available, including thermal imaging, GPS, ultrasound, magnetic sensors, optical sensors, and motion sensors [92]. For these purposes, researchers choose to rely on more robust external tracking systems [50,52], equipping the HMD devices with other sensors or motion capture systems such as Leap Motion or Microsoft Kinect. However, this frequently results in a restriction of the space available for the experience, because it becomes challenging to install large-scale systems and, also, allow multiple users to play simultaneously [53]. Another choice has been to use computer vision technologies such as the Vuforia Engine Library [32,35,72]; this approach allows the creation of MR experiences that interact with both the objects and the environment. However, tracking instability issues still persist, as image recognition can vary among tests as environmental conditions change [35]. To provide robustness even within widely varying environments both markerless and marker-based, XR tracking must take into account the brightness of the environment as well as the angle at which the camera is facing the marker, image, or object [24,35,36].

To retrieve data from the server, many XR headset-based applications require an Internet connection, which is not always available in all cultural heritage areas and sites. Other studies highlight the disadvantages of headsets in terms of battery life [69] and device cost [46]. Furthermore, not all heritage sites and museums have large enough spaces to accommodate the XR experience. This represents a limitation, necessitating the use of stratagems such as exploring the virtual space only with controllers or creating restricted play spaces [21,53].

5.3. User-related issues

One of the greatest challenges identified in the field of cultural heritage is user involvement. Several usability studies investigating the individual experiences of visitors who encountered XR solutions in exhibitions, museums, and heritage sites were carried out with a focus on how the users interacted with the headset and the environment prepared for the XR experience. The characteristics that researchers have mostly focused on concern user experience usefulness in the context of interest, ease of use of controllers and interfaces, and perceived enjoyment. Overall, the papers reported positive opinions of visitors toward the conducted XR experience, acknowledging the educational usefulness and immersive aspect of using headsets during the visit [18,23,40]. In addition, a predisposition to use these technologies regardless of the age of the visitors and their previous experience with XR technologies was reported, as well as requests to perform the experience again or in a different or extended version [39,44]. These outcomes highlight that the use of HMDs finds fertile ground in the field of cultural heritage, as it manifests itself as a useful tool for educating, communicating a message, and bringing people closer to culture and art appreciation. Researchers found that visitors perceived a greater sense of presence and immersion in visits that involved the use of XR technologies and that they further increased if the visual stimulus was accompanied by additional sensory stimuli, such as tactile and auditory stimuli [69]. The usage of tangible interfaces, where physical and virtual representations are perceptually coupled, has the potential to return the tactile feedback to the user naturally, reflecting the effects of manipulation on the virtual level, and consequently increasing the realism of interaction. A deeper understanding of the information on the exhibit can also be facilitated by visitors physically interacting with museum artifacts. However, developers must guarantee that the pace at which information is given in a particular moment is not overloaded and keeps the visitor focused on the experience.

An aspect to be considered with regard to the sense of presence is the realism of the reconstruction, both from the cultural-historical point of view and from that one of high fidelity in the reproduction of artifacts. In fact, the wealth of details in the simulations is much appreciated by the audience and contributes to the overall sense of immersion within the experience, confirming that high fidelity in the reproduction of places and artifacts is a fundamental requirement, especially when considering artifacts and details with which the user has to interact in a direct way and therefore should be visualized closely [33].

Another factor to consider is familiarity with the device. Cultural venues provide many users with the opportunity to try out new technology devices such as headsets and smart glasses for the first time. This may result in the lengthening of the expected time span for the experience, and longer waiting times for visitors [3]. Furthermore, there is still a strong commitment to the conventional notion of a museum, which comprises exposition rooms intended as works of art containers, in the modern socio-cultural framework [16]. Even if generally accepted by the public, research on these applications demonstrates that highly educated people have a superior understanding of how to use new technologies to promote culture [16], since they are more aware of the XR potential and, as a result, more prepared to reject the conventions established by traditional museums and adopt novel strategies for presenting the information. In this sense, the application layout can influence the perception of the user experience. Indeed, an unintuitive layout can negatively affect the user's concentration and worsen the virtual environment exploration. In order to satisfy users with little to no expertise and who may come from a variety of backgrounds, researchers must assure a high level of usability of their applications. This requirement is made much more relevant when considering that usually no prior training in the use of XR technologies is offered, in contrast to other fields like healthcare, industry, and military training.

A further issue with headset-based applications is that they are typically single-user experiences [59]. Again, this can result in long waits and force visitors to queue to try out the experience especially during peak times [53]. It may be beneficial to design waiting areas in which visitors are partially stimulated while queuing and partially prepared for the experience ahead of them, with a brief training on how to use the application [69].

Finally, the employment of XR technology in the field of cultural heritage raises privacy issues for users. The advantage of context-aware systems or content personalization is that they present the user with more pertinent content. The chance that these data may be lost or exploited increases as the system asks for more personal information about the user. For this reason, adequate security measures must be adopted to preserve the user's privacy, for instance following the indications provided by the General Data Protection Regulation (GDPR).

6. Conclusions

There has been increasing interest in the use of immersive reality technologies in the field of cultural heritage. This research contributes to the development and inclusion of AR, MR, and VR applications by providing an overview and analysis of relevant studies using fully immersive systems, such as headsets and CAVE systems, for solutions in the cultural heritage domain. Specifically, a lot of authors assessed the use of HMDs, headsets, and CAVE systems, emphasizing the advantages that they bring to the cultural heritage domain applications when compared to handheld devices, such as smartphones, tablets, and 2D monitors.

The effective use of these immersive systems in the cultural heritage field requires the development of customized technologies and product strategies that allows visitors to feel fully immersed and present in the virtual environment, allowing for an engaging and educational cultural experience that can enhance the quality and learning purposes of cultural visits.

By resolving issues through ongoing technological development, such as performance and computing power enhancement, design and interface implementation, battery life extension, and security improvements, more reliable and effective use will be feasible in the future.

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