

# NARRATIVE-DRIVEN XR FOR CULTURAL HERITAGE: A COMPARATIVE EVALUATION OF AUGMENTED AND VIRTUAL REALITY EXPERIENCES

*Paolo Clini\*, Renato Angeloni\*, Laura Coppetta\**

\*Università Politecnica delle Marche - Dipartimento di Ingegneria Civile, Edile e Architettura - Ancona, Italy.

## Abstract

This paper investigates the role of narrative-driven XR experiences in supporting cultural heritage interpretation through a comparative analysis of Augmented Reality (AR) and Virtual Reality (VR). Using the Church of Santa Maria in Muris (Italy) as a case study, two parallel experiences were developed. A user-centered evaluation approach was adopted to assess learning outcomes, engagement, usability, and perceived cultural value. Results show that both modalities effectively support comprehension and engagement, with AR enhancing contextual and exploratory learning through spatial integration within the physical environment, and VR providing a fully immersive and controlled virtual setting that supports a coherent and guided interpretation of narrative content. The findings highlight the complementary nature of AR and VR and the importance of narrative design, interaction, and spatial context in XR experiences.

## Keywords

Digital Replica, AI-assisted narrative guides, Extended Reality, UX evaluation, Cultural Heritage.

## 1. Introduction

Digital replicas, generative Artificial Intelligence (AI), and eXtended Reality (XR) technologies are increasingly assuming a central role in the processes of documentation, interpretation, and valorization of Cultural Heritage (CH). These tools prove especially effective in supporting the understanding and communication of contexts characterized by high stratigraphic and semantic complexity, whose interpretation is often challenging for non-expert users in the absence of appropriate mediation strategies.

Within this framework, the integration of digital surveying techniques, such as Structure-from-Motion (SfM) photogrammetry and Terrestrial Laser Scanning (TLS), enables the generation of three-dimensional models with high geometric and radiometric accuracy. These models serve not only as reliable records of the conservation state of cultural assets, but also as accurate digital replicas that can be reused across multiple applications. They provide a fundamental spatial and informational infrastructure for the development of immersive virtual environments, as well as for user tracking and spatial registration in AR applications, ensuring geometric

consistency and perceptual coherence between digital content and physical context.

At the same time, generative AI is emerging as a powerful tool for the production and dynamic adaptation of cultural content. Its application extends beyond automated text generation, which must nonetheless be grounded in rigorous validation processes based on verified historical sources, to the creation of interactive and adaptive content capable of responding to user behavior. In this perspective, AI enables the design of advanced narrative frameworks in which virtual entities, modeled as historical characters, act as cognitive and interpretative mediators within the User eXperience (UX).

The integration of high-fidelity digital replicas and AI-assisted narrative guides finds a natural application within XR technologies, particularly in AR for on-site experiences and VR for remote access. These two approaches define complementary yet methodologically distinct scenarios: AR maintains a strong connection with the physical environment, enhancing its perception through contextual digital augmentation, while VR enables fully immersive and controlled reconstructions, potentially including lost or no longer visible phases, thus

supporting processes of simulation and reinterpretation.

In light of these premises, this research aims to develop and evaluate two parallel experiences, one in AR and one in VR, applied to a specific case study, both structured around an interactive narrative mediated by AI-assisted narrative guides. The objective is to assess the effectiveness of these approaches in terms of user engagement, comprehension, and overall experience, also from a comparative perspective. Such effectiveness is not considered to depend solely on the level of immersion, but also on the quality of digital content, the coherence of the narrative structure, and the design of user interaction.

## 2. State of the art

The integration of digital surveying, XR technologies, and narrative-driven content has led to a progressive redefinition of how CH is documented and experienced. Within this framework, the transition from digital replicas generation to their deployment within XR environments has progressively consolidated into integrated methodological workflows, in which acquisition, processing, visualization, and interaction are closely interconnected. At the same time, the design of narrative structures and the evaluation of UX have emerged as fundamental components in shaping and validating the communicative and interpretative effectiveness of such systems.

### 2.1 From 3D Survey to Cultural Heritage Digital Replicas

Within the field of CH, the generation of digital replicas is grounded in the integration of surveying techniques, primarily based on SfM photogrammetry and TLS.

These methods enable the acquisition of highly detailed geometric and radiometric data, supporting the creation of accurate and reliable digital representations of heritage assets (Lo Pilato et al., 2023).

Photogrammetry has proven to be a flexible and efficient technique for CH documentation, allowing for the creation of detailed datasets even in complex or inaccessible contexts (Pepe et al., 2022; Saccucci & Pelliccio, 2025). Similarly, TLS provides highly accurate spatial information, contributing to the accurate reconstruction of

geometries and surface characteristics (Guarnieri et al., 2017).

Recent studies highlight the importance of combining multiple acquisition techniques to overcome the limitations of individual methods and achieve comprehensive and metrically reliable models.

The integration of photogrammetric data, UAV imagery, and TLS allows for the generation of dense and coherent point clouds, capturing both global morphology and fine details.

Such hybrid approaches have demonstrated their effectiveness in complex heritage scenarios, where different acquisition strategies are required to ensure completeness, accuracy, and efficiency of the survey process (Bertolini et al., 2024).

Following the data acquisition phase, which underpins the quality of digital replicas, particular attention must be given to data registration and processing to ensure an accurate representation (Clini, Nespeca, et al., 2025; Moga et al., 2022).

Subsequently, digital replicas must be optimized to be suitable for real-time applications, particularly within XR environments.

Optimization involves operations such as mesh editing and retopology, as well as texture baking, aimed at reducing computational complexity while preserving a high level of visual quality. In this sense, it represents a crucial step in bridging high-resolution survey data with their effective use within interactive and immersive systems (García-León et al., 2018; Gonizzi Barsanti et al., 2022; Jakob et al., 2015).

In this context, the reuse of digital assets across multiple applications has become increasingly relevant, highlighting the need for flexible and scalable workflows, as well as interoperable data structures, capable of supporting access, adaptation, and reuse without compromising content quality.

Accordingly, digital replicas should not be interpreted as final outputs, but rather as enabling infrastructures that support further applications, including visualization, analysis, and integration within immersive and interactive experiences.

In line with recent research, reuse can be understood as a key indicator of the value and impact of digital cultural heritage, reflecting its capacity to generate new knowledge, applications, and forms of engagement across different domains (Vasileva & Mc Neilly, 2024).

## 2.2 XR technologies for Cultural Heritage experiences

XR technologies have progressively emerged as key tools for enabling new forms of access to CH, supporting both on-site and remote experiences through the integration of digital content within real or fully virtual environments (Banfi et al., 2025). By combining spatial data, real-time rendering, and interactive interfaces, XR systems allow users to engage with cultural assets beyond the constraints of physical accessibility, conservation conditions, or visibility (Innocente et al., 2023; Singh et al., 2024).

From a technological perspective, XR applications can be distinguished into AR, Mixed Reality (MR), and VR, each characterized by specific affordances and limitations that directly influence the design of experiences (Bekele & Champion, 2019; Milgram & Kishino, 1994; Zhang et al., 2024). However, in relation to the objectives of this contribution, the focus will be placed specifically on AR and VR.

AR systems operate by overlaying digital information onto the physical environment, typically relying on tracking and registration techniques to align virtual content with the real world. This approach preserves the perceptual continuity of the site, enhancing user understanding through contextual augmentation while maintaining a direct connection with the physical asset (Alvarado, 2023; De-Dato et al., 2025; Koo et al., 2019; Souropetsis & Kyza, 2025).

In contrast, VR applications provide fully virtual environments in which users can explore reconstructed or simulated contexts. These environments are not constrained by the current state of the physical site and can therefore include lost, transformed, or hypothetical configurations, offering greater flexibility in spatial reconstruction and temporal representation. VR systems also allow greater control over visual and environmental conditions, enabling consistent immersive experiences regardless of external constraints (Theodoropoulos & Antoniou, 2022; Wang et al., 2024; Y. Zhao et al., 2025).

These technological differences entail distinct requirements in terms of interaction modalities, device performance, and user engagement. AR applications must address issues related to tracking accuracy, environmental variability, and real-time alignment with the physical context, while VR systems must ensure stable rendering

performance, intuitive navigation, and user comfort within fully virtual environments (Bekele et al., 2018). Consequently, the same digital content could be adapted to different platforms and usage scenarios, leading to diversified implementation strategies depending on the intended mode of access.

Within this framework, XR technologies should be understood as complementary systems rather than interchangeable solutions. Their effectiveness depends on their ability to support specific modes of access and interaction, whether rooted in the physical context or entirely detached from it, thus enabling a spectrum of cultural heritage experiences ranging from contextual augmentation to fully immersive virtual exploration.

## 2.3 Narrative Structures in XR for Cultural Heritage

While XR technologies enable immersive access to CH, the mere exploration of virtual or augmented environments does not necessarily support meaningful understanding. Several studies highlight that user engagement and learning are not guaranteed by immersion alone but depend on how content is structured and presented within the experience. In this sense, the organization of information and the design of narrative frameworks play a crucial role in guiding interpretation and supporting user comprehension (Galasso, 2025).

Narrative structures in XR can be understood as systems that organize cultural content across spatial and temporal dimensions, allowing users to access information progressively rather than through unstructured exploration. These structures may take different forms, including linear or non-linear sequences, spatially triggered content, and guided or semi-guided pathways. In CH applications, such approaches are particularly relevant in contexts characterized by stratification, fragmentation, or limited legibility, where users require interpretative support to reconstruct historical and spatial relationships (Clini et al., 2023; Gabellone & Desantis, 2025).

Within this framework, storytelling emerges as a key component in transforming digital replicas into meaningful cultural experiences. Rather than acting as a mere layer of additional information, narrative design contributes to establishing connections between past and present, enabling users to contextualize the heritage asset within

broader historical and cultural processes (Clini et al., 2024). This shift reflects a broader transition from technology-driven approaches toward interpretative models centered on UX and knowledge construction.

Different strategies can be adopted to deliver narrative content within XR environments. These include textual and audiovisual elements, spatial annotations, and guided experiences mediated by virtual elements such as avatars or digital characters. Virtual guides have been shown to support attention and comprehension, although their effectiveness depends strongly on factors such as positioning, activation mechanisms, and integration within the interaction flow (Sylaiou & Fidas, 2022). In this context, gamification strategies may further complement these approaches by structuring user interaction through challenges and rewards, fostering engagement while guiding the exploration of cultural content (Bozzelli et al., 2019; Sanfilippo et al., 2025).

Recent research has progressively explored the integration of AI within narrative systems, enabling the development of adaptive and interactive storytelling paradigms. Generative AI and large language models (LLMs) allow the creation of conversational agents capable of dynamically generating content and responding to user inputs, thus supporting more personalized and engaging experiences (Ariya et al., 2026; Natale et al., 2025). These systems can be configured as historical characters, virtual guides, or even narrative entities embedded within artifacts, shifting from static storytelling toward dialogic and participatory forms of interpretation (F. Gao et al., 2024).

However, within the scope of the present research, AI was primarily employed to support visual generation, voice synthesis, and character animation, rather than adaptive or conversational interaction systems.

Within the CH domain, AI-driven avatars have been investigated as mediators of knowledge, capable of simulating historical figures and delivering context-aware explanations grounded in curated datasets (Wilkinson et al., 2026). Approaches based on Retrieval-Augmented Generation (RAG) highlight the importance of anchoring generated content to verified sources to ensure historical accuracy and avoid distortions (DaCosta, 2025). At the same time, the use of conversational interfaces introduces new

opportunities for user engagement, allowing visitors to actively interact with cultural content through natural language queries and responses (H. Gao et al., 2024).

Beyond human-like avatars, recent studies propose extending narrative agency to cultural artifacts themselves, transforming them into entities capable of narrating their own history from a first-person perspective.

This approach enhances emotional engagement and supports experiential learning by fostering a more direct and empathetic relationship between users and heritage objects. Such perspectives align with broader trends in immersive storytelling, where narrative is distributed across multiple agents within the environment rather than centralized in a single guiding entity.

Moreover, the embodiment of AI within virtual avatars has been shown to significantly influence user engagement and perceived presence in XR environments, reinforcing the role of visual and interactive representation in narrative mediation. At the same time, multimodal interfaces combining voice, text, and embodied agents can improve both engagement and comprehension, suggesting that narrative effectiveness depends not only on content but also on its mode of delivery.

However, the integration of AI within narrative frameworks also raises critical issues related to authenticity, interpretative control, and epistemological reliability (Cirafici et al., 2025; Clini, Angeloni, et al., 2025). The behavior and output of generative systems are strongly influenced by design choices, including prompt engineering, data selection, and system constraints. As a result, AI-driven narratives should not be considered neutral, but rather as constructed representations that require careful validation and transparency, particularly in contexts where historical accuracy is essential.

Therefore, within XR applications for CH, narrative structures should be regarded as a core component, as they transform digital environments into interpretative systems capable of guiding users through complex cultural contexts. In this perspective, the integration of AI-driven narrative agents represents an evolution of traditional storytelling approaches, enabling more interactive, adaptive, and user-centered experiences, while simultaneously requiring rigorous methodological and ethical frameworks.

#### 2.4 Evaluating XR User Experience for Cultural Heritage

The evaluation of XR applications for CH has progressively shifted from technology-driven approaches toward user-centered methodologies, recognizing that the effectiveness of such systems cannot be assessed solely based on technical performance or visual realism (Konstantakis et al., 2018). A growing body of research instead emphasizes the importance of understanding how users perceive, interpret, and interact with digital content within immersive environments, highlighting the need for structured evaluation frameworks (Angeloni, 2022).

UX in XR is commonly analyzed through a multidimensional perspective that includes factors such as presence, engagement, perceived usefulness, learning outcomes, and overall satisfaction (Loureiro et al., 2020; Trunfio et al., 2022). These dimensions reflect the complexity of XR experiences, which combine perceptual, cognitive, and emotional components, and therefore require evaluation approaches capable of integrating both subjective perceptions and objective performance.

To address this complexity, recent studies propose multi-method evaluation strategies that integrate quantitative and qualitative approaches. These include objective measures, such as task completion time, error rates, and interaction patterns, alongside subjective assessments based on questionnaires, interviews, and observational protocols (Ntoa, 2025). Such approaches enable a more comprehensive understanding of user behavior and allow for the analysis of the relationship between system design and UX.

Within this context, empirical evaluation based on real users becomes essential, particularly when comparing different modes of access or interaction. In XR applications, immersion does not necessarily correspond to communicative effectiveness, and highly immersive environments do not automatically result in improved understanding or engagement. For this reason, controlled comparisons between alternative solutions are increasingly adopted to assess how different technological configurations influence user perception and experience.

Recent research also proposes interpretative models that describe XR experiences as the result of a balance between interaction, learning, system feedback, and emotional response, offering a

useful framework for analyzing the trade-offs between immersion, usability, and clarity of content (Gong et al., 2024; J. Zhao et al., 2025). At the same time, factors such as accessibility, sustainability, and inclusivity are gaining increasing relevance, highlighting the need to consider diverse user groups and long-term applicability in the design and evaluation of XR systems.

The evaluation of XR applications for CH should therefore be understood as an integral component of the design process, aimed at validating not only technological performance, but also the communicative, interpretative, and experiential effectiveness of the system. This approach supports the development of evidence-based strategies capable of guiding the design of meaningful and accessible heritage experiences.

#### 3. Research aims

Using the same cultural heritage site as a case study, this paper compares two XR experiences based on narrative content mediated by guiding avatars. Although both solutions were designed to communicate the historical and architectural values of the building, they differ in terms of device, level of immersion, and interaction modality. This comparison allows for the investigation of how different technological and experiential configurations influence users' access to, engagement with, and interpretation of digital cultural content.

The main objective of the study is to comparatively evaluate the effectiveness of the two experiences through a user-centered approach based on structured Likert-scale questionnaires. In particular, the analysis focuses on dimensions such as learning outcomes, experiential engagement, ease of interaction, and perceived cultural value, to assess whether different XR solutions produce different user responses when exposed to the same narrative content within the same cultural context.

In addition, the study examines aspects specific to the different modes of access, including the spatial integration of digital content within the real environment for the augmented reality experience, and perceived presence and realism in the virtual reality experience, together with factors related to comfort and ergonomics.

Within this framework, the research contributes to bridging the gap between narrative design and user experience evaluation in XR

applications for cultural heritage, a field that remains only partially explored through controlled comparative studies across different technological configurations.

A further objective is to provide a comparative framework to support the design of future applications for cultural heritage enhancement. The study therefore aims to identify strengths and limitations of each solution, offering insights to inform more conscious and sustainable design choices in relation to communicative goals, user engagement, and content accessibility.

#### 4. Material and methods

##### 4.1 Case study

The case study selected for this research is the Church of Santa Maria in Muris (Fig. 1), today known as San Simone, located in Belmonte Piceno (Marche, Italy). The building, recognized as a national monument, stands on a hill at 263 m above sea level, in a strategic panoramic position along the route connecting the Sibillini Mountains to the Adriatic coast. Its location, between the Tenna and Ete valleys and close to the ancient route leading towards the area known as Le Morrecini, reinforces its role as a landmark within a historically significant rural and territorial system.

The site is characterized by significant historical stratification and architectural complexity. The structure preserves evidence of the reuse of Roman materials and constructions, including a funerary inscription embedded in the façade, associated with a Roman cinerary urn dedicated by Florio Ottato to himself and to his wife Rufria Prima, as well as other archaeological fragments and sculpted marbles reused in the masonry. Its current layout reflects a medieval configuration dating back to the 10th century, with elements associated with the early Romanesque architecture of the region. The building also preserves features typical of early medieval and Romanesque architecture, such as small round-arched windows, a simple and functional spatial organization, and the use of full-centre arches. Historical information regarding the origin and management of the complex is mainly derived from Farfa documentation, which records its donation to the monastic community and its integration into the Benedictine network, with implications for the organization of the surrounding rural landscape.



**Fig. 1:** Main façade of the Church of Santa Maria in Muris, Belmonte Piceno, Italy

From an architectural perspective, the building is distinguished by a façade tower, interpreted as a possible Lombard element later modified, and by the presence of an internal cryptoporticus beneath the tower, characterized by spatial configurations of particular interest. The tower, positioned at the centre of the façade, gives the building a distinctive vertical profile and has been associated with Germanic and Lombard architectural models, while the small internal portico beneath it has been described as a rare feature in comparison with other Romanesque buildings. Overall, the church represents a significant example of settlement continuity and historical-constructive stratification. This continuity is expressed through the sequence of transformations from a Roman funerary context to a Christian sacred building, to a medieval monastic and territorial landmark.

Due to these characteristics, the site presents challenges in terms of legibility and interpretation, especially for non-expert visitors. The relationships between different historical phases and architectural elements are not always immediately understandable through direct observation, thus requiring interpretative support. In particular, the coexistence of Roman spolia, possible Lombard elements, Romanesque architectural features, Farfa-related historical

documentation, and later restorations produces a dense and multilayered narrative that is difficult to perceive without mediation.

This makes the site particularly suitable for the application of XR technologies, as immersive and spatially situated narratives can support users in reconstructing temporal and spatial relationships. In this context, the use of avatar-mediated storytelling enables the distribution of information across multiple points of interest, aligning narrative content with specific locations within the architectural space (Fig. 2). Such an approach allows visitors to connect material evidence (e.g. the façade inscription, sculpted fragments, tower, internal portico, and spatial orientation of the church) with the broader historical processes that shaped the monument and its landscape.

The selection of this case study therefore provides an appropriate framework for evaluating how different XR configurations, while presenting the same narrative content, affect UX, learning processes, and the overall interpretation of the CH asset. At the same time, Santa Maria in Muris offers a particularly meaningful testing ground because its heritage value depends not only on individual architectural features, but also on the interpretation of long-term transformations involving settlement, religion, landscape, and local identity.

#### 4.2 Digital Documentation and 3D Reconstruction

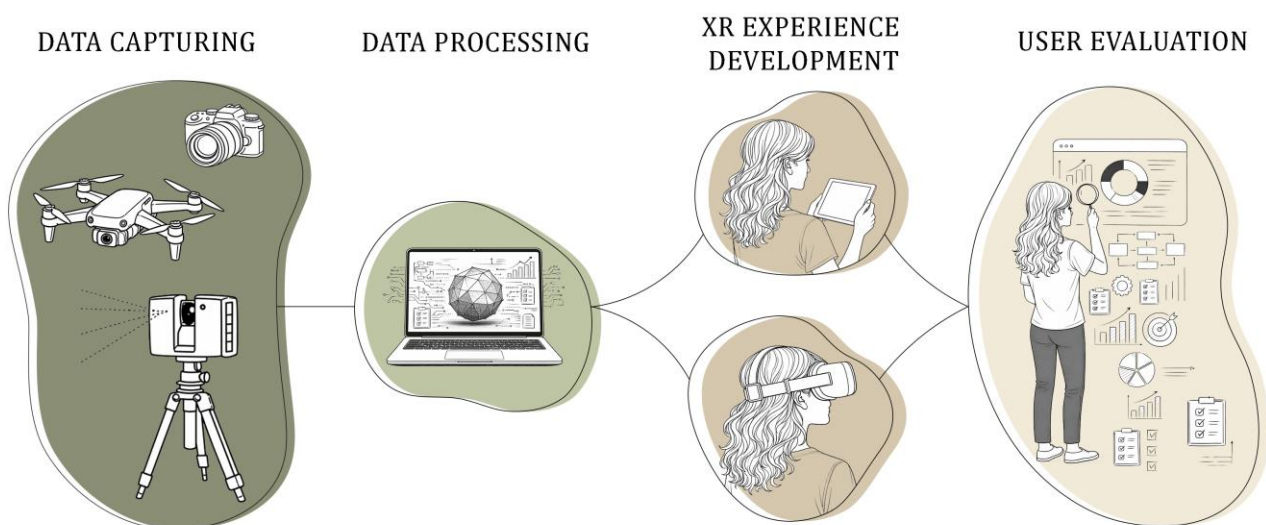
To achieve comprehensive documentation of the building, the data acquisition process was

carried out through an integrated survey methodology aimed at generating a three-dimensional model that is accurate in terms of both geometry and color.

TLS was performed using a Leica RTC360, acquiring data both inside and outside the church, including, where accessible, the interior space of the bell tower. A total of 32 scans were carried out, distributed to ensure complete coverage of the surfaces visible from the ground and adequate overlap between scan stations. For the chromatic documentation of surfaces, high-resolution images were acquired using a Sony ILCE Alpha 9 camera: 185 for the interior spaces and 295 for the exterior surfaces. This approach was adopted to overcome the limitations in resolution and quality of the panoramic images acquired by the internal camera of the TLS.

To document the roofing system and portions not accessible from the ground, such as the rear façade of the bell tower, a UAV survey was conducted using a DJI Matrice 4E, acquiring 436 aerial images. The integration of terrestrial and UAV data made it possible to overcome accessibility constraints and ensure complete coverage of the architectural envelope.

The laser scans were registered using Register 360+, while the photographic datasets were processed in Agisoft Metashape by organizing the images into three distinct groups: aerial images, terrestrial images of the interior, and terrestrial images of the exterior. Using the TLS point cloud as a metric reference, all datasets were aligned within a common reference system.



**Fig. 2:** Workflow of the adopted methodology, from data capturing and processing to XR experiences development and user evaluation

The geometric reconstruction was primarily based on TLS data, considered more accurate from a metric perspective, while the UAV dataset was used exclusively to integrate portions not captured from the ground. The external TLS point cloud was therefore integrated with the one derived from UAV images, removing redundant data in areas already reconstructed through laser scanning.

Starting from the resulting point clouds, high-resolution mesh models (highpoly) were generated and subsequently cleaned and optimized through topological correction, removal of unwanted elements, and hole filling. For the interior spaces, the mesh was generated exclusively from TLS data. The models were then re-imported into the photogrammetric environment for the texturing phase, using UAV and terrestrial images for the exterior and terrestrial images for the interior, to achieve consistent and high-quality material representation.

For the development of XR applications, an optimization phase for real-time environments was required. A quad-based retopology process was applied, reducing the polygon count while preserving the morphological coherence of the architecture.

Retopology and the transfer of textures and normal maps from the high-poly to the low-poly model were carried out in Blender using baking techniques. This process allowed the preservation of visual detail while significantly reducing the computational load of the model.

The resulting low-poly models are metrically consistent with the original survey data and optimized for visualization on mobile devices and immersive headsets, providing the basis for the development of the XR experiences (Fig. 3).

#### 4.3 Narrative Design and XR Experience

The narrative design was developed based on the historical analysis of the church and the main transformations that have affected the building over time. On this basis, six characters were defined, each associated with a specific historical phase and conceived as a narrative voice representing distinct moments in the life of the site.

The narrative was structured through a workflow inspired by audiovisual pre-production processes, articulated into four phases: script development, storytelling definition, storyboard creation, and animatics production (Fig. 4).

The experience was conceived as a guided visit, in which the narrative is mediated by characters and supported by visual elements aimed at facilitating content comprehension. In this way, the narrative structure organizes the experience into coherent sequences, supporting user orientation and enabling the construction of relationships between historical events and architectural space.

The characters were defined based on the historical reconstruction of the site, identifying figures relevant to the interpretation of its different phases. Using generative AI tools, each character was assigned a visual identity and a voice consistent with both the narrative and the historical context, with visual appearances generated using ChatGPT, voice synthesis developed through ElevenLabs, and character animations and movements implemented using HeyGen (Fig. 5).

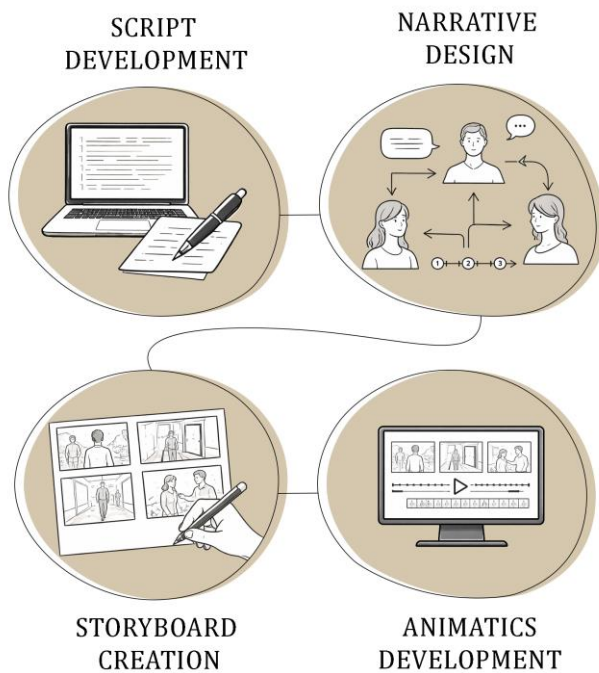
The narrative is therefore mediated by a system of guiding avatars that accompany the user in the exploration of the Church of Santa Maria in Muris. The archaeologist guide introduces the experience, presenting the site as a place where history, landscape, and memory intertwine. The subsequent characters represent different phases of the site's history: a Roman veteran recalls the ancient origins of the site and the funerary inscription embedded in the tower; a monk narrates the construction of the medieval church and the reuse of Roman structures; a Lombard master builder explains the meaning of the façade tower; Countess Albagia refers to the donation of the church to the Abbey of Farfa and the transformations related to territorial organization; finally, the painter Antonio Liozzi recounts the history of the 18th-century altarpiece and its later rediscovery.

The transition between narrative stages is mediated by symbolic objects associated with each character. In particular, the Roman veteran is linked to a helmet, the monk to a cross, the builder to a hammer, the countess to a parchment, and the painter to a palette. These elements function as narrative activation devices, guiding the user through the progression of the experience and structuring the interaction flow.

Both the AR and VR experiences were developed using the Unity cross-platform game engine. In the case of AR, a mobile application for Android and iOS devices supports user tracking both inside and outside the church.



**Fig. 3:** External and internal views of the low-poly model after baking operations. Top right: detail showing a comparison between the high-poly, low-poly, and textured low-poly models.



**Fig. 4:** Narrative workflow structure: script development, narrative design, storyboard creation, and animatics development



**Fig. 5:** Set of narrative characters developed for XR experiences

The TLS data were used as a spatial reference for the AR environment, enabling alignment between digital content and the real space thanks to the MultiSet Unity SDK. Once the application is launched and the required permissions are granted, the user is guided by the archaeologist avatar, who introduces the experience and activates an exploratory dynamic based on the search for symbolic objects within the real environment. The discovery of each object triggers

the appearance of the corresponding avatar, which delivers context-specific narrative content related to the user’s position and the represented historical phase. When the application is launched outside the site, the experience is reconfigured into a remote mode, allowing access to the content through a guided selection of characters (Fig. 6).

The VR experience, developed for Meta Quest 3 headsets, is structured as an immersive environment articulated into multiple scenes. After an initial setup and interaction training phase, the user accesses a virtual reconstruction of the church exterior and subsequently its interior. As in the AR experience, exploration is guided by the search for symbolic objects that activate the different narrative avatars, following a consistent interaction logic. However, unlike AR, VR enables a fully immersive experience of the digitally reconstructed space, independent of the user’s physical presence at the site and characterized by greater control over navigation and interaction within the virtual environment.

This configuration also allows specific architectural elements to be highlighted in relation to the narrative, such as the Roman inscription on the façade tower, the carved representation of Saint Michael the Archangel, and the altarpiece (Fig. 7).

Although both experiences share the same narrative structure and content, they differ in terms of access modality, relationship with space, and level of immersion, thus representing two complementary approaches to CH mediation through XR technologies.

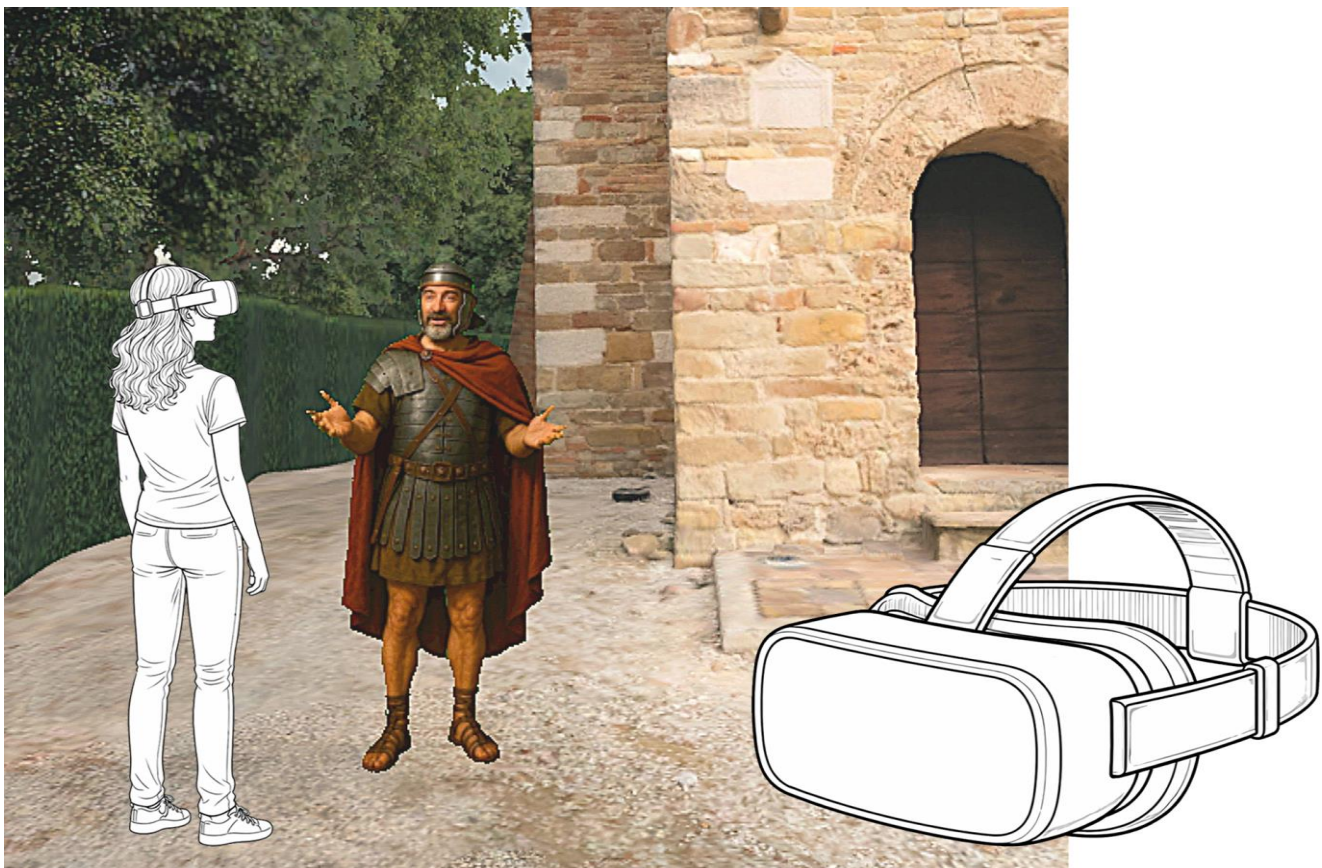
#### 4.4 User Experience evaluation

To evaluate the effectiveness of the two applications, a questionnaire was administered to users at the end of the experience. The aim was to assess content comprehension, user engagement, ease of use, and overall satisfaction.

The questionnaire was structured into two main sections (Tab. 1). The first section collected participants’ profile data, including age group, familiarity with digital tools, and prior experience with augmented or virtual reality. The second section was based on a five-point Likert scale (1 = not at all; 5 = very much). For each dimension, at least one negatively worded item was included in order to reduce automatic or acquiescent responses and to verify the consistency of participants’ evaluations.



**Fig. 7:** AR experience: visualization of the historical character within the real environment through a mobile device



**Fig. 7:** VR experience: interaction with a virtual character within the immersive reconstructed environment

**Tab. 1:** Interview items addressing the overall experience and dimensions investigated by the questionnaire

Target	Age		
	How comfortable do you feel using digital tools (apps, tablets, video games)? Have you used AR or VR experiences before?		
Learning Outcomes	The experience helped me understand the historical evolution of the place over time. Dividing the narrative among different historical characters made the chronological sequence of events clearer. The explanations provided by the avatars were clear and understandable. The experience helped me connect historical events with the spaces of the church. I had difficulty following the narrative thread from one character to another.		
	Experiential Engagement	The experience was engaging. The transition from one character to another kept my curiosity alive. I maintained a high level of attention throughout the entire experience. I felt actively involved in building my own visiting path. The experience felt repetitive or not very stimulating.	
		Interaction Usability	It was easy to understand what to do to use the experience. It was easy to understand how to activate the content at the points of interest. I always understood how to continue the path after each story ended. I felt that I could control the pace and progression of the experience. I found the experience frustrating.
			Perceived Cultural Value & Satisfaction

The dimensions considered include learning outcomes, experiential engagement, interaction satisfaction. In particular, the questionnaire assessed users' understanding of the historical evolution of the site, the clarity of the narrative, the level of engagement throughout the experience, the ease of interaction with the content, and the perceived value of the experience in terms of cultural heritage enhancement.

In addition to these common sections, two specific modules were included according to the mode of access: for the AR experience, a section focused on the spatial integration of digital content within the real environment (Tab. 2); for the VR

experience, a module addressing perceived presence, environmental realism, usability and comfort, and potential cybersickness effects (Tab. 3).

**Tab. 2:** AR-specific questionnaire items related to the spatial integration of digital content within the real environment

Augmented Spatial Integration	The avatars seemed to belong to the real space of the church. Placing the content in specific locations made the narrative more meaningful. The positioning of the digital content was stable and coherent as I moved through the real place. The experience improved my perception of the real place during the visit. The digital content seemed out of place or disconnected from the real architectural context.
-------------------------------	----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------

**Tab. 3:** VR-specific questionnaire items related to presence, environmental realism, usability, comfort, and cybersickness

Virtual Spatial Presence & Realism	I had the feeling of actually being inside the church. The virtual environment felt realistic (space, proportions, materials). I felt immersed in the virtual environment during the experience. Placing the avatars in specific locations within the virtual environment made the narrative more meaningful. The virtual environment seemed artificial or not very believable.	
	Comfort, Ergonomics & Cybersickness	I found it comfortable to wear and use the headset throughout the entire experience. The VR interactions felt natural and easy to perform. I experienced physical discomfort (nausea, dizziness, headache) during the experience. I experienced visual fatigue or eye discomfort. I felt safe while moving and exploring the virtual space.

The evaluation involved voluntary participants who experienced either the AR or the VR application. No specific expertise in digital technologies or CH was required, allowing for the inclusion of users with different levels of familiarity with XR systems. Each participant was asked to complete the experience individually. In the case of AR, the experience was conducted on-site, while the VR application was accessed in a controlled indoor environment using a Meta Quest 3 headset.

At the end of the experience, participants were asked to complete the questionnaire. The data collected were anonymized and used to analyze differences in user experience across the two XR modalities, with particular attention to the

relationship between interaction modality, level of immersion, and content comprehension.

In addition to descriptive statistics and internal consistency analysis through Cronbach's alpha, inferential statistical comparisons between the AR and VR groups were conducted using the Mann-Whitney U test on the questionnaire dimensions shared by both experiences. The test was selected due to the ordinal nature of Likert-scale data and the independent structure of the two user groups.

## 5. Results and discussion

The analysis of the questionnaire responses related to both the AR and VR experiences (N = 31 for each) shows overall positive evaluations across all considered dimensions, confirming the effectiveness of the proposed XR applications in supporting learning, engagement, interaction, and perceived cultural value. Despite sharing the same narrative structure and content, the two modalities exhibit distinct patterns in user experience, reflecting the influence of interaction design and spatial context on content interpretation.

The internal consistency of the questionnaire was assessed using Cronbach's alpha for each dimension. In the AR experience, good reliability was observed for interaction usability ( $\alpha = 0.80$ ) and perceived cultural value and satisfaction ( $\alpha = 0.87$ ), while experiential engagement and spatial integration showed moderate reliability ( $\alpha \approx 0.64$ ). A lower value was recorded for learning outcomes ( $\alpha = 0.30$ ), suggesting a more heterogeneous structure of this dimension, likely due to the multifaceted nature of learning processes in situated environments. In contrast, the VR experience demonstrated generally higher and more balanced reliability, with good values for learning outcomes ( $\alpha = 0.82$ ), experiential engagement ( $\alpha = 0.80$ ), and perceived presence ( $\alpha = 0.79$ ), and moderate values for interaction usability ( $\alpha = 0.69$ ), perceived cultural value ( $\alpha = 0.64$ ), and comfort-related aspects ( $\alpha \approx 0.66$ ), indicating a more coherent response pattern across users.

Inferential statistical comparisons conducted through the Mann-Whitney U test did not reveal statistically significant differences between the AR and VR groups across the shared questionnaire dimensions ( $p > 0.05$ ). Although descriptive trends suggest different interaction dynamics and spatial perceptions between the two modalities, the

results indicate that both experiences achieved comparably positive evaluations in terms of learning outcomes, engagement, usability, and perceived cultural value.

In both experiences, participants reported a high level of understanding of the historical evolution of the site and the relationship between architectural space and historical events.

The character-based narrative structure proved effective in organizing information chronologically and supporting content comprehension, with limited difficulty in following the narrative progression.

Both modalities were also perceived as engaging and capable of maintaining users' attention throughout the experience. However, the nature of engagement differed between the two approaches.

In AR, engagement was strongly connected to the interaction with the real environment, where the search for symbolic objects reinforced the relationship between digital content and physical space. In VR, engagement was mainly driven by immersion and continuity within the reconstructed virtual environment.

Interaction usability received positive evaluations in both modalities. The AR experience was generally perceived as intuitive and easy to use. In VR, usability showed slightly greater variability, likely influenced by differences in users' familiarity with immersive technologies and the cognitive demands of virtual navigation.

Similarly, both experiences achieved high levels of perceived cultural value and satisfaction, with users recognizing their effectiveness in enhancing the understanding of the heritage site. AR was more frequently associated with contextual integration within the real environment, whereas VR provided a stronger sense of immersion and perceptual involvement.

The comparison between the two modalities highlights their complementary characteristics. AR supports contextualized and exploratory forms of learning through the direct integration of digital content within the physical environment. VR, on the other hand, provides a fully immersive and controlled setting that facilitates a more guided and coherent interpretation of narrative content. These findings suggest that the effectiveness of XR experiences depends not only on immersion itself, but also on the relationship between narrative structure, interaction design, and spatial configuration.

## 6. Conclusions

This study investigated the role of narrative-driven XR experiences in supporting the interpretation of CH, through the comparative analysis of two applications based on the same content but implemented in augmented and virtual reality. By adopting a user-centered evaluation framework, the research aimed to understand how different technological configurations influence learning processes, engagement, and user perception.

The results demonstrate that both AR and VR can effectively support the communication of CH when grounded in a well-structured narrative framework. The use of guiding avatars and character-based storytelling proved to be a valuable strategy for organizing complex historical information and facilitating user comprehension.

The comparison between the two modalities highlights their complementary nature. AR reinforces the relationship between digital content and the physical environment, supporting situated and exploratory learning processes. VR, on the other hand, enables engagement within a fully virtual and controlled environment, facilitating a structured and coherent interpretation of narrative content.

These findings confirm that the effectiveness of XR applications does not depend solely on the level of immersion, but rather on the interplay between

narrative structure, interaction design, and spatial configuration.

From a methodological perspective, the study contributes to current research on XR for cultural heritage by combining digital survey methodologies, narrative design, immersive technologies, and UX evaluation within a single comparative framework. Future developments may explore hybrid AR/VR solutions, adaptive AI-assisted narrative systems, and broader user studies involving larger and more diversified samples. Although the adopted sample size proved adequate for an exploratory comparative study, larger participant groups would allow more robust statistical analyses and improve the generalizability of the observed trends.

### *Acknowledgment*

The authors would like to thank the Marche Region and the Municipality of Belmonte Piceno for supporting the “Digital Belmonte” initiative and the dissemination of the XR experiences presented in this study through the official platform: <https://visitbelmontepiceno.it/digital-belmonte/>. The related digital services were developed by UNILAS – Piccola Università del Lavoro Sociale, under commission from the Municipality of Belmonte Piceno within the PR MARCHE FESR 2021/2027 programme for integrated digital public services.

## REFERENCES

- Angeloni, R. (2022). Digitization and Virtual Experience of Museum Collections. The Virtual Tour of the Civic Art Gallery of Ancona. *SCIRES-IT - SCientific RESearch and Information Technology*, 12(2), 29–42. <https://doi.org/10.2423/i22394303v12n2p29>
- Ariya, P., Worragin, P., Khanchai, S., Poollapalin, D., & Julrode, P. (2026). Voice, text, or embodied AI avatar? Effects of generative AI interface modalities in VR museums. *Informatics*, 13(3), 42. <https://doi.org/10.3390/informatics13030042>
- Banfi, F., Cazzani, A., & Liu, W. (2025). XR technologies for enhanced cultural engagement: From HBIM to a comparative analysis of VR and WebVR development tools. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-M-9-2025, 95–102. <https://doi.org/10.5194/isprs-archives-XLVIII-M-9-2025-95-2025>
- Bekele, M. K., & Champion, E. (2019). A comparison of immersive realities and interaction methods: Cultural learning in virtual heritage. *Frontiers in Robotics and AI*, 6, 91. <https://doi.org/10.3389/frobt.2019.00091>
- Bekele, M. K., Pierdicca, R., Frontoni, E., Malinverni, E. S., & Gain, J. (2018). A survey of augmented, virtual, and mixed reality for cultural heritage. *Journal on Computing and Cultural Heritage*, 11(2), 7:1–7:36. <https://doi.org/10.1145/3145534>
- Beltran Alvarado, G. A. B. (2023). Augmented Reality (AR) in education, medicine and industry: a systematic review of literature. *SCIRES-IT - SCientific RESearch and Information Technology*, 13(1), 153–166. <https://doi.org/10.2423/i22394303v13n1p153>
- Bertolini, S., Piemonte, A., Caroti, G., Bevilacqua, M. G., Capriuoli, F., Rinaldi, E., Santillo, D., & Muccilli, I. (2024). Integrated 3D survey methodologies and digital platforms for the enhancement of archaeological data in the digital transition. *SCIRES-IT - SCientific RESearch and Information Technology*, 14(2), 107–124. <https://doi.org/10.2423/i22394303v14n2p107>
- Bozzelli, G., Raia, A., Ricciardi, S., De Nino, M., Barile, N., Perrella, M., Tramontano, M., Pagano, A., & Palombini, A. (2019). An integrated VR/AR framework for user-centric interactive experience of cultural heritage: The ArkaeVision project. *Digital Applications in Archaeology and Cultural Heritage*, 15. <https://doi.org/10.1016/j.daach.2019.e00124>
- Cirafici, A., Langella, C., Palmieri, A., & Giordano, G. (2025). AI and Digital Technologies for a New Narrative of Archaeological Heritage. *SCIRES-IT - SCientific RESearch and Information Technology*, 15(2), 19–34. <https://doi.org/10.2423/i22394303v15n2p19>
- Clini, P., Angeloni, R., D'Alessio, M., Coppetta, L., & Galli, I. (2025). Digital representation and AI-driven virtual experience for historic houses: The case study of Borgo Storico Seghetti Panichi. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-M-9-2025, 337–344. <https://doi.org/10.5194/isprs-archives-XLVIII-M-9-2025-337-2025>
- Clini, P., Angeloni, R., D'Alessio, M., & Ferretti, U. (2024). Narrare l'inaccessibile: Un virtual immersive movie per le grotte di Palazzo Campana. In *Misura/Dismisura: ideare, conoscere, narrare. 45° Convegno internazionale dei docenti delle discipline della rappresentazione. Congresso della Unione Italiana per il Disegno* (pp. 2647–2666). <https://doi.org/10.3280/oa-1180-c604>
- Clini, P., Angeloni, R., D'Alessio, M., & Quarchioni, R. (2023). Enhancing onsite and online museum experience through digital reconstruction and reproduction: The Raphael and Angelo Colocci temporary exhibition. *SCIRES-IT - SCientific RESearch and Information Technology*, 13(2), 71–84. <https://doi.org/10.2423/i22394303v13n2p71>

- Clini, P., Nespeca, R., Ferretti, U., Galazzi, F., & Bernacchia, M. (2025). Inclusive museum engagement: Multisensory storytelling of Cagli Warriors' journey and the Via Flamina landscape through interactive tactile experiences and digital replicas. *Heritage*, 8(2), 61. <https://doi.org/10.3390/heritage8020061>
- DaCosta, B. (2025). Speaking with the past: Constructing AI-generated historical characters for cultural heritage and learning. *Heritage*, 8(9), 387. <https://doi.org/10.3390/heritage8090387>
- De-Dato, P., Hernández-Navarro, Y., & Cantatore, E. (2025). Conserving architectural heritage through hybrid strategies and open technologies in the phygital era. *SCIRES-IT - SCIENTIFIC RESEARCH AND INFORMATION TECHNOLOGY*, 15(2), 121–136. <https://doi.org/10.2423/i22394303v15n2p121>
- Gabellone, F., & Desantis, V. (2025). A philological approach for the 3D reconstruction of the Messapian walls of Manduria in an augmented reality project. *SCIRES-IT - SCIENTIFIC RESEARCH AND INFORMATION TECHNOLOGY*, 15(2), 35–52. <https://doi.org/10.2423/i22394303v15n2p35>
- Galasso, F. (2025). Digital narratives for the enhancement of minor historical heritage. *SCIRES-IT - SCIENTIFIC RESEARCH AND INFORMATION TECHNOLOGY*, 15(2), 85–102. <https://doi.org/10.2423/i22394303v15n2p85>
- Gao, F., Fang, K., & Chan, W. K. (2024). Humanizing artifacts: An educational game for cultural heritage artifacts and history using generative AI. In *CHI-PLAY Companion 2024 - Companion Proceedings of the Annual Symposium on Computer-Human Interaction in Play* (pp. 91–96).. <https://doi.org/10.1145/3665463.3678792>
- Gao, H., Lindquist, M., & Serrano Vergel, R. (2024). AI-driven avatars in immersive 3D environments for education workflow and case study of the Temple of Demeter, Greece. *Journal of Digital Landscape Architecture*, 9, 640–651. <https://doi.org/10.14627/537752059>
- García-León, J., Sánchez-Allegue, P., Peña-Velasco, C., Cipriani, L., & Fantini, F. (2018). Interactive dissemination of the 3D model of a Baroque altarpiece: A pipeline from digital survey to game engines. *SCIRES-IT - SCIENTIFIC RESEARCH AND INFORMATION TECHNOLOGY*, 8(2), 59–76. <https://doi.org/10.2423/i22394303v8n2p59>
- Gong, Q., Zou, N., Yang, W., Zheng, Q., & Chen, P. (2024). User experience model and design strategies for virtual reality-based cultural heritage exhibition. *Virtual Reality*, 28(2), 69. <https://doi.org/10.1007/s10055-024-00942-z>
- Gonizzi Barsanti, S., Guagliano, M., & Rossi, A. (2022). 3D reality-based survey and retopology for structural analysis of cultural heritage. *Sensors*, 22(24), 9593. <https://doi.org/10.3390/s22249593>
- Guarnieri, A., Fissore, F., Masiero, A., & Vettore, A. (2017). From TLS survey to 3D solid modeling for documentation of built heritage: The case study of Porta Savonarola in Padua. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2-W5, 303–308. <https://doi.org/10.5194/isprs-archives-XLII-2-W5-303-2017>
- Innocente, C., Ulrich, L., Moos, S., & Vezzetti, E. (2023). A framework study on the use of immersive XR technologies in the cultural heritage domain. *Journal of Cultural Heritage*, 62, 268–283.. <https://doi.org/10.1016/j.culher.2023.06.001>
- Jakob, W., Tarini, M., Panozzo, D., & Sorkine-Hornung, O. (2015). Instant field-aligned meshes. *ACM Transactions on Graphics*, 34(6), 189. doi:10.1145/2816795.2818078
- Konstantakis, M., Aliprantis, J., Teneketzis, A., & Caridakis, G. (2018). Understanding user experience aspects in cultural heritage interaction. In *Proceedings of the 22nd Pan-Hellenic Conference on Informatics* (pp. 267–271). <https://doi.org/10.1145/3291533.3291580>

- Koo, S., Kim, J., Kim, C., Kim, J., & Cha, H. S. (2019). Development of an augmented reality tour guide for a cultural heritage site. *Journal on Computing and Cultural Heritage*, 12(4), 21. <https://doi.org/10.1145/3317552>
- Lo Pilato, A., Scandurra, S., Palomba, D., & Di Luggo, A. (2023). Valorizing cultural heritage by employing digital technologies for survey and communication: The Church of San Vincenzo Ferreri. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-M-2-2023, 969–975. <https://doi.org/10.5194/isprs-Archives-XLVIII-M-2-2023-969-2023>
- Loureiro, S. M. C., Guerreiro, J., & Ali, F. (2020). 20 years of research on virtual reality and augmented reality in tourism context: A text-mining approach. *Tourism Management*, 77, 102120. <https://doi.org/10.1016/j.tourman.2019.104028>
- Milgram, P., & Kishino, F. (1994). A taxonomy of mixed reality visual displays. *IEICE Transactions on Information and Systems*, 77(12), 1321–1329  
[http://vered.rose.utoronto.ca/people/paul\\_dir/IEICE94/ieice.html](http://vered.rose.utoronto.ca/people/paul_dir/IEICE94/ieice.html)
- Moga, E. S., Hernández-Muñoz, Ó., & Sánchez-Ortiz, A. (2022). 3D scanning for comparative analysis of manufacture and deterioration tracking: A case study of the 18th century wax Venus de' Medici. *SCIRES-IT - SCientific RESearch and Information Technology*, 12(1), 1–18.
- Natale, S., Surace, B., Mensa, E., & Befera, L. (2025). ChatGPT for cultural heritage and the customization of generative AI: A talkthrough analysis of the Luigi Einaudi chatbot. *New Media & Society*. <https://doi.org/10.1177/14614448251384258>
- Ntoa, S. (2025). Usability and user experience evaluation in intelligent environments: A review and reappraisal. *International Journal of Human-Computer Interaction*, 41(5), 2829–2858. <https://doi.org/10.1080/10447318.2024.2394724>
- Pepe, M., Alfio, V. S., & Costantino, D. (2022). UAV platforms and the SfM-MVS approach in the 3D surveys and modelling: A review in the cultural heritage field. *Applied Sciences*, 12(24), 12866. <https://doi.org/10.3390/app122412886>
- Saccucci, M., & Pelliccio, A. (2025). SFM as visual enargeia of damage in paintings. *SCIRES-IT - SCientific RESearch and Information Technology*, 15(1), 131–140. <https://doi.org/10.2423/i22394303v15n1p131>
- Sanfilippo, F., Tataru, M., Hua, M. T., Johansson, I. J. S., & Andone, D. (2025). Gamifying cultural immersion: Virtual reality and mixed reality in city heritage. *IEEE Transactions on Games*, 17(4), 893–911. <https://doi.org/10.1109/TG.2025.3553712>
- Singh, P., Pahuja, N., Kansal, M., Gurung, S., Shukla, U., & Gupta, S. (2024). Enhancing tourism experiences and preserving cultural heritage with AR and VR. In *2nd International Conference on Disruptive Technologies, ICDT 2024* (pp. 225–231). <https://doi.org/10.1109/ICDT61202.2024.10489490>
- Souropetsis, M., & Kyza, E. A. (2025). CompARe: Design and development of a gamified augmented reality learning environment for cultural heritage sites. *Journal on Computing and Cultural Heritage*, 18(1), 14. <https://doi.org/10.1145/3703917>
- Sylaiou, S., & Fidas, C. (2022). Virtual humans in museums and cultural heritage sites. *Applied Sciences*, 12(19), 9913. <https://doi.org/10.3390/app12199913>
- Theodoropoulos, A., & Antoniou, A. (2022). VR games in cultural heritage: A systematic review of the emerging fields of virtual reality and culture games. *Applied Sciences*, 12(17), 8476. <https://doi.org/10.3390/app12178476>

Trunfio, M., Della Lucia, M., Campana, S., & Magnelli, A. (2022). Innovating the cultural heritage museum service model through virtual reality and augmented reality: The effects on the overall visitor experience and satisfaction. *Journal of Heritage Tourism*, 17(1), 1–19. <https://doi.org/10.1080/1743873X.2020.1850742>

Vasileva, S., & McNeilly, N. (2024). *Measuring the instances and value of digital cultural heritage reuse*. L'Aia, Paesi Bassi: Europeana Foundation.

Wang, H., Gao, Z., Zhang, X., Du, J., Xu, Y., & Wang, Z. (2024). Gamifying cultural heritage: Exploring the potential of immersive virtual exhibitions. *Telematics and Informatics Reports*, 15, 100150. <https://doi.org/10.1016/j.teler.2024.100150>

Wilkinson, C. M., Roughley, M., Liu, C. Y. J., Shrimpton, S., Davidson, C., & Dickinson, T. (2026). The affordances of AI-powered, deepfake, avatar creator systems in archaeological facial depiction and the related changes in the cultural heritage sector. *Applied Sciences*, 16(2), 1023. <https://doi.org/10.3390/app16021023>

Zhang, J., Wan Yahaya, W. A. J., & Sanmugam, M. (2024). The impact of immersive technologies on cultural heritage: A bibliometric study of VR, AR, and MR applications. *Sustainability*, 16(15), 6446. <https://doi.org/10.3390/su16156446>

Zhao, J., Ma, Y., Zhang, X., Lin, H., Lu, Y., Wu, R., . . . Zou, F. (2025). An empirical study on the impact of different interaction methods on user emotional experience in cultural digital design. *Sensors*, 25(17), 5273. <https://doi.org/10.3390/s25175273>

Zhao, Y., Li, Y., Dai, T., Sedini, C., Wu, X., Jiang, W., . . . LC, R. (2025). Virtual reality in heritage education for enhanced learning experience: A mini-review and design considerations. *Frontiers in Virtual Reality*, 6, 1560594. <https://doi.org/10.3389/frvir.2025.1560594>