



Grand Challenges in Immersive Technologies for Cultural Heritage

Hanbing Wang, Junyan Du, Yue Li, Lie Zhang & Xiang Li

To cite this article: Hanbing Wang, Junyan Du, Yue Li, Lie Zhang & Xiang Li (27 Mar 2025): Grand Challenges in Immersive Technologies for Cultural Heritage, International Journal of Human-Computer Interaction, DOI: [10.1080/10447318.2025.2475996](https://doi.org/10.1080/10447318.2025.2475996)

To link to this article: <https://doi.org/10.1080/10447318.2025.2475996>



© 2025 The Author(s). Published with license by Taylor & Francis Group, LLC.



Published online: 27 Mar 2025.



Submit your article to this journal [↗](#)



Article views: 31



View related articles [↗](#)



View Crossmark data [↗](#)

Grand Challenges in Immersive Technologies for Cultural Heritage

Hanbing Wang^a , Junyan Du^a , Yue Li^b , Lie Zhang^a , and Xiang Li^{c,d} 

^aInstitute of Interactive Media, Academy of Fine Arts, Tsinghua University, Beijing, China; ^bDepartment of Computing, Xi'an Jiaotong-Liverpool University, Suzhou, China; ^cDepartment of Engineering, University of Cambridge, Cambridge, UK; ^dLeverhulme Centre for the Future of Intelligence, University of Cambridge, Cambridge, UK

ABSTRACT

Cultural heritage, a testament to human history and civilization, has gained increasing recognition for its significance in preservation and dissemination. The integration of immersive technologies has transformed how cultural heritage is presented, enabling audiences to engage with it in more vivid, intuitive, and interactive ways. However, the adoption of these technologies also brings a range of challenges and potential risks. This paper presents a systematic review, with an in-depth analysis of 177 selected papers. We comprehensively examine and categorize current applications, technological approaches, and user devices in immersive cultural heritage presentations, while also highlighting the associated risks and challenges. Furthermore, we identify areas for future research in the immersive presentation of cultural heritage. Our goal is to provide a comprehensive reference for researchers and practitioners, enhancing understanding of the technological applications, risks, and challenges in this field, and encouraging further innovation and development.

KEYWORDS

Immersive technologies; cultural heritage; Grand challenges; literature review; virtual reality; mixed reality

1. Introduction

The United Nations Educational, Scientific and Cultural Organization (UNESCO) aims to promote the identification, protection, and preservation of cultural and natural heritage worldwide, recognizing sites of outstanding value to humanity.¹ Nowadays, the use of immersive technologies in cultural heritage displays has increasingly become the focus of academic research, as institutions seek to enhance visitor engagement and broaden access to valuable artifacts and experiences (Bekele et al., 2018). These immersive displays combine technologies such as virtual reality (VR), augmented reality (AR), mixed reality (MR), and other platforms like 360-degree video and interactive digital installations, enabling audiences to experience cultural heritage—here encompassing both tangible and intangible forms—in more vivid, intuitive, and personal ways. However, the adoption of these technologies also introduces several risks and challenges.

In the realm of immersive technologies for cultural heritage, prior studies have explored a variety of issues. Some research emphasizes digital preservation and conservation (Evens & Hauttekeete, 2011), while others focus on specific applications of immersive technologies or isolated aspects of cultural heritage (Baratin et al., 2023; Beraldin et al., 2005; Boboc et al., 2022; Buragohain et al., 2024; Chong et al., 2021; He et al., 2024; Idris et al., 2016; Innocente et al., 2023; Koller et al., 2009; Windhager et al., 2019). However, certain works neglect to address the challenges or negative

impacts—often referred to as the “dark sides”—associated with these technologies (Bekele & Champion, 2019; Kukreja et al., 2024; Nofal et al., 2017; Wagner & De Clippele, 2023; Zhang, 2024). Additionally, in many cases, the application of immersive technologies to cultural heritage is restricted to VR, AR, and MR (Zhang et al., 2024). Furthermore, some studies rely on samples that predate 2018 (Bekele et al., 2018; Piccialli & Chianese, 2017), or their sample sizes are too small to draw broader conclusions (Piccialli & Chianese, 2017).

Given these gaps, it is necessary to conduct a new survey of the literature on immersive technologies for cultural heritage. This review will place particular emphasis on the grand challenges of applying immersive technologies to digital cultural heritage, offering a critical reflection on their impact in this field.

In this paper, we set the stage for a comprehensive review of the literature on immersive technologies in cultural heritage. Our review covers a pool of 5368 articles published up to January 27 2024, sourced from leading databases including the ACM Digital Library, IEEE Xplore, and Scopus. From this, we systematically analyzed 177 papers to identify these papers according to three main categories: “device,” “application,” and “technology.” Based on our analysis, we identified and summarized the strengths of the equipment, applications, and technologies, which can be grouped into the following areas: enhancing participation and experience,

CONTACT Xiang Li  xl529@cam.ac.uk  Department of Engineering, University of Cambridge, Cambridge, UK; Leverhulme Centre for the Future of Intelligence, University of Cambridge, Cambridge, UK

© 2025 The Author(s). Published with license by Taylor & Francis Group, LLC.

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. The terms on which this article has been published allow the posting of the Accepted Manuscript in a repository by the author(s) or with their consent.

fostering social engagement, advancing education and knowledge dissemination, optimizing technological implementation, and promoting heritage protection and transmission.

We also identified and categorized the shortcomings of the equipment, applications, and technologies, focusing on aspects such as technical barriers, sustainability, user experience, and safety concerns. Additionally, we found certain areas that have not been fully explored in the research, which could have a significant impact on the digital display and dissemination of cultural heritage. These gaps include the potential misinterpretation of cultural heritage, the influence on media purity, and the possible potential damage to cultural heritage.

By exploring these diverse dimensions, our goal is to offer a comprehensive reference that will inform both researchers and practitioners, supporting more informed decision-making and fostering innovative solutions in the field of cultural heritage preservation in the digital age.

2. Background

2.1. Research status of cultural heritage immersion technology

Immersive technology blurs the boundary between the physical and virtual worlds, allowing users to experience a heightened sense of immersion (Lee et al., 2013). This category includes AR, VR, MR, as well as haptic technology, remote immersion, and more (Suh & Prophet, 2018). Immersive technology captures an individual's physical movements, posture, and gestures as inputs, which are then used to interact with the virtual environment, making the user feel as if they are truly present in that environment (Handa et al., 2012). When applied to the display of cultural heritage, immersive technologies enhance the quality and dissemination of cultural content by stimulating our senses in a more vivid and natural way (Innocente et al., 2023).

To understand the current state of immersive technology research in the context of cultural heritage, we conducted two searches on Google Scholar. The first search used the keywords "CULTURAL HERITAGE" and "IMMERSIVE TECHNOLOGY," while the second search added "CHALLENGE" to refine the focus. From these searches, we selected relevant literature review articles. By analyzing these articles, we aimed to develop a comprehensive understanding of the research landscape. However, these review articles present several limitations:

- They primarily focus on issues related to digital preservation and protection, rather than the presentation aspect of cultural heritage (Evens & Hautekeete, 2011).
- They discuss only specific applications of immersive technology or focus on isolated aspects of cultural heritage, without providing a broader perspective (Baratin et al., 2023; Beraldin et al., 2005; Boboc et al., 2022; Buragohain et al., 2024; Chong et al., 2021; Idris et al., 2016; Innocente et al., 2023; Koller et al., 2009; Windhager et al., 2019).

- They do not address the challenges or negative implications of the technologies (Bekele & Champion, 2019; Kukreja et al., 2024; Nofal et al., 2017; Wagner & De Clippele, 2023; Zhang, 2024).
- The immersive technologies applied to cultural heritage are restricted to VR, AR, and MR (Zhang et al., 2024).
- Much of the literature was published before 2018 (Bekele et al., 2018; Piccialli & Chianese, 2017), or the sample sizes in some studies were too small (Piccialli & Chianese, 2017).

Evens and Hautekeete identify four major issues hindering the sustainability of digital preservation in cultural heritage institutions (Evens & Hautekeete, 2011). Boboc and Chong focus on the application of AR to cultural heritage, with Boboc identifying eight key topics (Boboc et al., 2022; Chong et al., 2021), while Buragohain explores the challenges and strategies of digitization in the metaverse (Buragohain et al., 2024). Idris discusses the technical challenges of protecting intangible cultural heritage (Idris et al., 2016), and Koller examines the research challenges in digital archives for 3D cultural relics (Koller et al., 2009). Beraldin highlights the opportunities and challenges introduced by recent 3D technologies for heritage conservation and virtual reconstruction (Beraldin et al., 2005), while Windhager tackles the difficulties in visualizing collected data (Windhager et al., 2019), and Baratin examines issues related to disseminating technical content (Baratin et al., 2023).

Several studies discuss the use of advanced digital technologies in cultural heritage but overlook challenges or negative aspects. Zhang promotes the potential of digital technologies without addressing limitations (Zhang, 2024), Bekele compares immersive reality technologies without exploring challenges (Bekele & Champion, 2019), and Wagner addresses legal issues but not practical challenges (Wagner & De Clippele, 2023). Nofal and Kukreja delve into "digital heritage" and its applications but avoid discussing the "dark side" of these technologies (Nofal et al., 2017; Kukreja et al., 2024), while Innocente identifies limitations in the field without covering negative implications (Innocente et al., 2023).

Zhang provides a bibliometric analysis of VR, AR, and MR technologies applied to cultural heritage but limits the discussion to these technologies (Zhang et al., 2024). Bekele offers an analysis of immersive technologies in cultural heritage from before 2018, noting potential barriers but missing recent advancements (Bekele et al., 2018). Piccialli summarizes 12 papers published in 2016, offering an overview rather than in-depth analysis (Piccialli & Chianese, 2017).

2.2. Application of immersive technology in cultural heritage

The application of immersive technologies such as VR, AR, MR, and 360-degree video experiences has become an increasingly important area of research in cultural heritage, with a focus on enhancing visitor engagement and expanding access to artifacts and experiences. This section reviews

key literature, covering the use of immersive technology in environmental reconstruction, data protection, visitor experience, education, and storytelling.

Kersten et al. (2018) highlight the role of immersive technology in environmental reconstruction, outlining a two-part workflow: 3D data recording and VR system development, which includes motion navigation, interaction, and multi-user design. Their work compares user experiences in virtual and real-world environments, showcasing how immersive technology connects the virtual with the physical world (Kersten et al., 2018). Similarly, Hassani emphasizes the role of digital technologies in speeding up data collection, recording, and ensuring precise outputs for heritage documentation (Hassani, 2015).

For virtual tours of fragile or hard-to-reach historical sites, Ruffin and Permadi explore how immersive technologies, such as VR models, enhance inclusivity by overcoming access barriers for people with disabilities and the elderly (Ruffino et al., 2019). Their attention to audience participation, including the use of binaural audio for realistic soundscapes, offers a more humanistic approach to virtual heritage experiences (Ruffino et al., 2019).

On a larger scale, Argyriou et al. combine 360-degree immersive video with gamification and narrative-driven virtual experiences to create interactive urban environments (Argyriou et al., 2020). They argue that combining high participation through narrative and freedom through movement technology leads to deeper, long-lasting audience engagement (Argyriou et al., 2020).

In cultural heritage education, Anastasovitis and Roumeliotis advocate for immersive technology to provide safe, controlled environments for both learners and heritage sites (Anastasovitis & Roumeliotis, 2020). VR is used, for example, to train underwater archaeologists in excavation tasks while protecting fragile artifacts (Anastasovitis & Roumeliotis, 2020). These technologies also allow for remote learning and virtual visits, proving valuable in situations where physical access is restricted (Anastasovitis & Roumeliotis, 2020).

Overall, immersive technologies are proving successful in enhancing visitor experience and education in cultural heritage, though the literature suggests varying levels of adoption across sectors, pointing to the need for more standardized reviews and practices.

2.3. Challenges and limitations

While immersive technologies offer significant potential for the digital display of cultural heritage, they present several challenges and limitations.

One major issue is the digital divide and unequal access to advanced technology. Hassani notes that cultural heritage professionals must continually update their skills to manage digital projects effectively (Hassani, 2015). However, knowledge gaps between heritage experts, IT specialists, and surveyors, as well as disparities across different regions and socio-economic groups, exacerbate the digital divide (Hassani, 2015). Storeide et al. highlighted data

heterogeneity and interoperability challenges (Storeide et al., 2023). Differences in how virtual and real-world research emphasize either observer perception or quantitative parameters can lead to issues with the authenticity and integrity of digital representations (Storeide et al., 2023). As a result, it is often difficult to reuse data across different applications due to incompatible formats, and current standards fail to ensure uniform measurements and workflows (Storeide et al., 2023).

User experience and technology adaptation also pose challenges. Argyriou et al. emphasized the need to improve user comfort by addressing factors such as high-resolution video, smooth navigation, and guided interfaces (Argyriou et al., 2020). However, too much guidance can reduce immersion, and finding the right balance between comfort and immersion remains an ongoing challenge.

Regarding cultural appropriation and the commercial use of digital heritage have also arisen. Klinowski and Szafarowicz discuss conflicts between copyright, ownership, and public versus commercial interests in the digitization of cultural heritage (Klinowski & Szafarowicz, 2023). This illustrates that balancing the rights of creators and owners with public access and commercial use could still be a major challenge. However, the potential of digital approaches to promote wider access and create business opportunities still requires validation through further empirical research.

These challenges highlight the need for a careful, balanced approach when adopting immersive technologies in cultural heritage, ensuring that technological progress supports rather than undermines cultural preservation.

2.4. Research gaps and emergent strategies

Despite the growing literature on the use of immersive technologies in various fields, there are still significant gaps in comprehensive, systematic reviews that focus specifically on their use in cultural heritage. Previous surveys have often touched on the potential and benefits of these technologies, but have largely overlooked a systematic exploration of the associated challenges and negative aspects, particularly the unintended consequences of digitization on cultural heritage. These include, but are not limited to, issues such as digital dependence and resistance, social ethics in the digital context, and the misinterpretation of cultural heritage caused by its diverse digital representations. Another concern is the impact of digital technology on the “purity of media experience” in presenting cultural heritage. This concept refers to the authenticity and immediacy with which audiences engage with cultural heritage. Ideally, this experience should reflect the original historical and sensory context, without significant mediation or alteration. When individuals engage with cultural heritage, the goal is for them to encounter it in its unaltered form, minimally influenced by interpretive layers, technological enhancements, or information filtering. This principle emphasizes that the processes of media translation and interpretation should not substantially distort the original essence of cultural heritage. Further, the use of digital display technologies in cultural heritage can have

potentially damaging effects, including physical damage, light and noise pollution, historical and cultural distortions, and threats to privacy and data security.

Existing reviews of the relationship between immersive technology, cultural heritage and people have often focused on specific aspects of research on how technology helps people to enhance their understanding of cultural heritage, but in our view this is not a comprehensive definition of the relationship between the three. For example, Bentley et al. describe the relationship between digital technology, the field of artificial intelligence, and people (Bentley et al., 2024). They identify social factors, as well as digital engagement factors under the influence of digital technologies and digital perception and experience factors as digital confidence that can influence people's attitudes toward AI (Bentley et al., 2024). Throughout the paper, the definition of the relationship between the three is expressed as a pattern of interdependence, which is often overlooked in the study of immersive technology and cultural heritage (Bentley et al., 2024). Similarly, future research should focus on digital dependence and resistance under the influence of immersive technology, which may have an impact on the understanding of cultural heritage.

Moreover, the social injustices that exist in digital discourse should not be ignored. Johnson focused on the infiltration and substitution of social identity into technology, including the role presetting of gender, race, class, educational background and other factors (Johnson, 2004). That is, the maximum value of technological progress is defined as being associated with white, middle class, and male, and the technical, scientific, and logical disciplines are also considered to be gender-related. Under such a trend, the development direction of technological progress will be further restricted, and the protection and dissemination of cultural heritage will also fall into a single situation. The research perspective of this paper complements our work by focusing on the dark side of the intersection between immersive technology and cultural heritage, without addressing the ethical issues underlying the development of either technology.

There is a clear need for urgent strategies aimed not only at harnessing the positive potential of these technologies, but also at mitigating their adverse effects. This study will focus on identifying and developing such strategies, with an emphasis on improving the efficacy of immersive technologies in cultural heritage, while addressing the ethical, social and technological challenges they pose. This approach will contribute to a more nuanced understanding of the role of digital technologies in cultural preservation and engagement, providing a balanced perspective that can guide future implementation and policy development.

3. Method

With the aim of identifying and examining the latest status of research in the digital applications of cultural heritage up to 2024, we chose to conduct a scoping review. The purpose of the scope review is to “provide an initial delineation and assessment of the potential size and coverage of the existing

research literature.” Although the issues concerned in systematic reviews are usually relatively precise, for example, the existing reviews in relevant fields usually focus on the current status of the application of cultural heritage in a specific field, which is a scope-defining review, lacking a comprehensive and systematic research perspective exploration that includes all the applications of cultural heritage technologies. They will clearly present and organize the relevant field evidence found, and analyze existing research and contributions under specific topics. In this paper, we conduct research that is up-to-date in time and relatively larger in scope, rather than proposing solutions to specific problems. For this reason, we limit our literature screening to the full text of papers and scope review of the technologies, applications and devices of cultural heritage.

3.1. Research questions and rationale

This review is guided by the following research questions (RQs):

- What types of equipment are primarily used, and what technologies are commonly employed when interacting with digital displays of cultural heritage?
 - For example, are VR headsets or AR glasses more commonly used in museum installations?
 - What role do motion sensors or interactive touchscreens play in enhancing user engagement with cultural heritage artifacts?
- What are the key application areas developed in this context?
 - For instance, are these technologies primarily applied in education, tourism, or preservation of intangible heritage such as traditional crafts or oral history?
- What potential challenges or negative impacts arise from the use of immersive technologies in cultural heritage?
 - Examples could include ethical concerns over the representation of sensitive cultural materials or the long-term preservation of digital installations themselves.
 - Additionally, there may be technical limitations such as high costs or a lack of accessibility for certain audiences.

3.2. Search strategy

3.2.1. Identify keywords

At the beginning of the search, we tested the search results by browsing a large number of relevant articles on Google Scholar and trying to use some high-frequency words as keywords. Notably, to avoid subjective interference, we chose to be data-driven by searching for roots such as “IMMERSION” and “INTERACTION.” Therefore, “CULTURAL HERITAGE” AND “TECHN*” AND (“DIGITAL” OR IMMERSI* OR “MULTIMEDIA” OR INTERACTI*) were finally selected as keywords for this review. This means that we will have access to most of the data related to this set of words without bias in retrieval due to our linguistic predisposition and knowledge background.

After defining the keywords related to the digitization of cultural heritage, we searched through the keywords. ACM

Digital Library, IEEE Xplore and Scopus databases are widely used in data retrieval of core papers and have gained high evaluation in the industry. Therefore, we used the above databases to retrieve 339, 520 and 4509 articles on ACM Digital Library, IEEE Xplore and Scopus, accordingly (5368 articles in total).

3.2.2. Search

We searched ACM Digital Library, IEEE Xplore, Scopus databases using the OR operator and the AND operator between keywords within each set. Since the search form of each database is different, we give the same keyword format of the three databases slightly different when searching. We limit our search to an article's title, abstract, and author keywords.

3.2.3. Preliminary literature format screening

Before the first round of screening, we first removed some records that did not meet the criteria from the retrieved papers, including records that were flagged as unqualified by the automated tool, duplicate records, and records that were deleted for other reasons. The purpose of this process is to improve the efficiency of data refinement screening by screening and removing targets that do not meet the criteria. Then, we use the filter to search the database and get ACM Digital Library (205), IEEE Xplore (513), and Scopus Search (3822). The search logic we use is to remove papers of low value or interference such as posters, short papers, abstract papers, and copyright notices.

3.3. First screening

After combining the search results from the three databases, we obtained 3907 articles as a sample for the first round of screening. For these objects, we use Excel tables for manual screening, which is divided into three stages of the screening process. In the first stage, we screened the articles for language and excluded 1836 articles written in non-English. Of the 2071 surviving papers, we have only retained 1448 journal papers. After checking 623 English conference papers, we found problems such as changing the name of the conferences, co-organizing the conferences, and stopping the conferences. For this reason, we believe that research based on conference papers is not very reliable, so journal papers are listed as the main body of our research. In the third stage, 382 journal papers were retained by screening papers based on page count, impact factor, citations, word of mouth, retractions, or duplication factors.

3.4. Filtering by article content

In this stage, we mainly screened the full-text content. We condensed the 382 papers to 177 according to three evaluation criteria: term application, keyword correlation, and content coverage, and entered the final systematic study. Figure 1 details the complete process from launching the search to identifying the papers included in the analysis. Based on our research questions, we defined the following exclusion (EC) and inclusion (IC) criteria:

EC1. Reviews or literature reviews: Reviews, literature reviews, and opinion articles are excluded. The purpose of this study is to analyze specific cases and original research, not to summarize or review existing review studies.

EC2. Key terms missing: If relevant key terms (e.g., AR, VR, immersive technologies, etc.) are not mentioned in the article, they are excluded. This reflects that the article may not be relevant to the research topic.

EC3. Inappropriate Use of Terminology: If the description or application of digital technology in the article is not consistent with the context in which cultural heritage is displayed, it is excluded. For example, if the "metadata" discussed in the article is used only for general information management or data storage, and does not relate to its application in the presentation of cultural heritage, such as to enhance the accessibility of cultural heritage materials, improve the interactivity of content or enrich the visitor experience, then such use is considered an inappropriate use of the term. Because it does not properly reflect the important role and potential value of metadata in the display of cultural heritage. Similarly, if the technology is used for gamified learning or the simple presentation of cultural heritage content without an in-depth discussion of its specific application and impact in the presentation of cultural heritage, the article does not meet the research criteria.

EC4. Lack of correlation between digital technology and cultural heritage display: If the application of digital technology in the field of cultural heritage display is not explicitly discussed in the article, even if digital technology (e.g., AR, VR, etc.) is mentioned, it will be excluded. This is because a reference to digital technology without exploring its specific application and impact in the display of cultural heritage does not meet the core concerns of this study. For example, articles that focus on the protection of cultural heritage rather than its display, or discuss technologies that have a direct link to the display of cultural heritage, will also be excluded.

EC5. Marginal references to digital technology: Articles will be excluded if the reference to digital technology is only superficial, such as a brief mention in the abstract or introduction, or if the application of digital technology is weakly linked to the display of cultural heritage and does not constitute the main content of the article. This criterion aims to ensure that the included articles focus on the practical application and in-depth analysis of digital technologies in the presentation of cultural heritage.

EC6. Data set introduction: If the article mainly introduces data sets but does not explicitly mention immersive or emerging technologies, the article will be excluded.

EC7. Lack of information: An article will be excluded if it does not provide enough detailed information to allow the full application of the coding standard.

IC1. Innovative applications of technology: Articles should show how emerging technologies (e.g., artificial intelligence, AR, VR, etc.) can be applied to the presentation and experience of cultural heritage. This includes, but is not limited to,

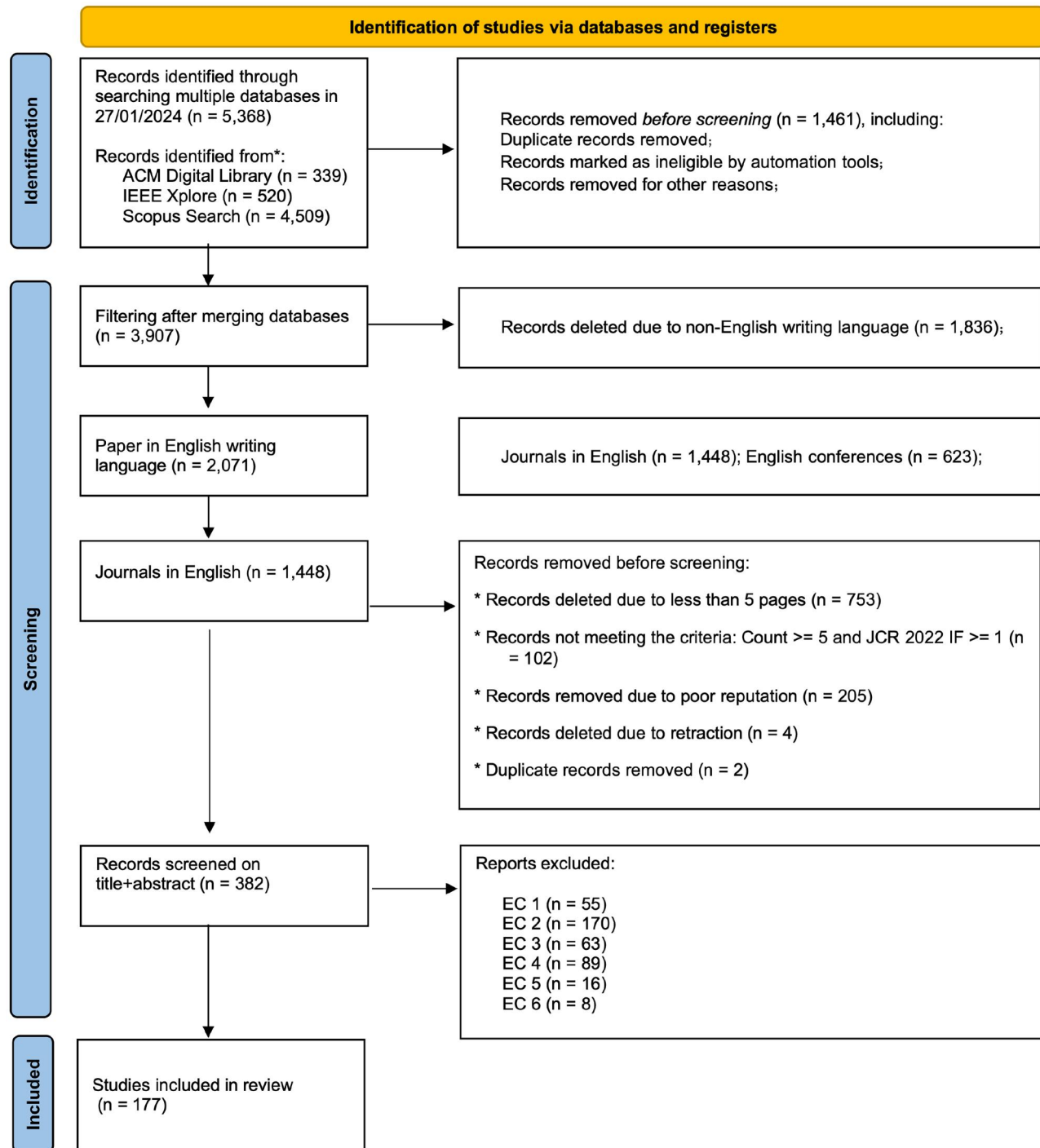


Figure 1. PRISMA Flow diagram illustrating the identification, screening, and inclusion process of studies for a systematic review. Initially, 5368 records were identified through searches in multiple databases (ACM digital Library, IEEE Xplore, and Scopus). After the removal of 1461 duplicates and non-relevant entries, 3907 records were further filtered. Records written in non-English languages were excluded ($n = 1836$), leaving 2071 papers. A total of 1448 journal papers and conference proceedings were screened, and additional exclusions were made based on criteria such as page length, impact factor, and paper quality. 177 studies were finally included in the review.

innovative applications of technology in cultural heritage, ways to enhance interactive experiences, and the application of new technologies in cultural heritage education.

IC2. Integration of technology and cultural heritage: Research should explore new ways of integrating technology and cultural heritage, such as recreating historical scenes through AR, or using VR to display cultural sites that are not physically accessible.

IC3. User Interaction and Experience: includes studies that focus on how users interact with cultural heritage enhanced by technology. This may involve the evaluation of user experience, innovation in interactive design, or research into how users perceive and understand cultural heritage through technology.

IC4. Application-oriented research: Consider those studies in which the application of technology is not a primary

research focus but plays a key role in the presentation of cultural heritage. For example, a project that uses AR to aid history education, or a study that applies machine learning techniques to analyze cultural heritage data.

IC5. Articles requiring further reading: If, at the time of initial reading of the abstract, it is not clear whether the articles meet the inclusion criteria, we will include them for the second stage of screening.

For the process of the literature screening, we employed a multi-step approach that included independent screening by multiple authors, as well as a review by a panel of 20 experts. These experts, comprising cultural heritage presentation practitioners, university scholars, and professionals from cultural heritage protection institutions, were invited to assess and discuss the initial selection results. Their involvement enhances both the objectivity and credibility of the screening process. Additionally, an anonymized table (see Table 1) will be included in the manuscript, providing background information on these 20 experts, such as their role, gender, years of experience (categorized as senior [> 15 years] or junior [< 5 years]), and professional background (i.e., academic, industry, and public sector). This information is included to ensure greater transparency regarding the composition and expertise of the panel.

3.5. Critical appraisal, potential bias, and limitations

The scope of the sample should be limited by a more comprehensive consideration of all available types of evidence in content, without limiting the breadth of evidence sources due to methodological quality. However, in order to obtain a relatively more manageable set of papers, we included only complete thesis proceedings and journal publications in the final sample range. Apart from these screenings, we did not exclude papers based on their methodological quality.

The keyword determination process may be influenced by the specific papers in the research base. In addition, it is difficult for the keywords we have chosen to cover all articles in

the relevant field, so the existing list may carry a subjective understanding of this field of study. But because we use root search, which avoids the limitations of subjectivity to some extent, we are confident that we can find most relevant papers. But this approach also leaves us with a large sample of false positives. To reduce errors in the screening and coding stages, we used the first round of a three-stage screening process to eliminate as many errors as possible. Our aim is to cover the latest extensive research in the field of digital display of cultural heritage. In addition, we conducted extensive discussion sessions to resolve conflicts and fine-track exclusion/inclusion criteria, keyword descriptions, screening processes (two one-hour initial screening sessions, three one-hour full-text screening and data extraction sessions).

4. Results

4.1. Paper review

4.1.1. Research direction

Based on the final corpus of 177 unique papers, we found four research directions. First of all, the largest proportion of papers are those with a specific research project as the core research object. These papers focus on the application of cultural heritage digitization strategies in specific scenarios and aim to explore a comprehensive analytical framework for practical application. For example, by building a digital platform for cultural heritage, HeGO, users can use their uploaded images to build three-dimensional reconstructions of sites and apply them to implement social media games (Fontanella et al., 2021).

Second, methodological framework research, mainly discusses the solution of a kind of cultural heritage digital display problems. For example, Suominen et al propose an approach to play culture's internal and external cultural heritage, discussing the relationship between history, cultural heritage and digital technology through a four-fold table of the relationship between cultural heritage (or history) and digital technology (Suominen & Sivula, 2013). Third, discuss the application of a new technology in the application of

Table 1. Anonymized background information of the 20 experts in the review panel.

Expert	Gender	Age	Role	Background	Experience
1	Male	55	Professor	Academic	Senior
2	Female	36	PhD Student	Academic	Senior
3	Female	31	Historian	Academic	Junior
4	Male	33	Architectural Restorer	Academic	Junior
5	Male	46	Cultural Creative Company Owner	Industry	Senior
6	Female	41	Heritage Site Manager	Public Sector	Senior
7	Male	34	Heritage Site Interpreter	Public Sector	Senior
8	Male	29	Local Museum Staff	Public Sector	Junior
9	Male	30	National Museum Staff	Public Sector	Junior
10	Female	35	Cultural Heritage Column Website Manager	Industry	Junior
11	Female	36	Cultural Heritage Column Reporter	Industry	Senior
12	Male	37	Associate Professor	Academic	Senior
13	Male	38	Local Museum Staff	Public Sector	Senior
14	Male	44	Vice President of Cultural Creative Group	Industry	Senior
15	Male	45	Local Museum Staff	Public Sector	Senior
16	Female	40	Local Museum Staff	Public Sector	Senior
17	Male	44	Local Museum Staff	Public Sector	Senior
18	Female	35	Local Museum Staff	Public Sector	Junior
19	Male	40	Researcher	Academic	Senior
20	Female	33	Local Museum Staff	Public Sector	Junior

multiple projects. Ardito et al. for example, propose ways to identify and specify the attributes of Internet of Things (IoT) devices through user-defined semantics in order to make it easier for cross-domain experts to operate the technology and apply IoT technology more smoothly in the field of cultural heritage (Ardito et al., 2020). Fourth, the smallest proportion of literature review studies. Hou et al. for example, outline the models, techniques, and practices that drive the digitized life of intangible cultural heritage resources, looking at several key but less researched tasks such as digital archiving, computational coding, conceptual representation, and interactive engagement with intangible cultural elements to identify advancements and gaps in existing conventions (Hou et al., 2022).

4.1.2. Publication venue

A focus on publication venues can quickly determine the distribution of core journals within the field. According to the cumulative number of published papers, these papers were published in several publishing places, among which the most common five were *Journal on Computing and Cultural Heritage* (35), *Journal of Cultural Heritage* (22), *Digital Applications in Archaeology and Cultural Heritage* (12), *Personal and Ubiquitous Computing* (12), and *Heritage Science* (11).

4.2. Visual analysis

4.2.1. Sample classification analysis

We have carefully read and studied the full text of the 177 papers selected finally. We studied these papers according to three main categories: “device,” “application,” and “technology.”

Device refers to the devices used by the audience in the usage scenario mentioned in the paper. For example, Hulusic mentioned in the article that Tangible User Interfaces (TUI), in which users interact with the virtual cultural heritage application through the actual operation of the interface, can be summarized in the “mobile/PC/LAPTOP” category (Hulusic et al., 2023). According to the data analysis, we mainly extracted a total of 199 frequency articles mentioned about equipment in the article. These include AR and VR devices, touchable and interactive user interface devices, mobile and portable devices, data acquisition scanning and printing devices, sensors and computing devices, projection and mapping technology devices, photography, and video capture. Among them, the most widely used are AR and VR devices, which are mentioned 58 times, accounting for 29.1%. VR devices account for the largest proportion. In addition, data acquisition, 3D scanning and printing equipment were also mentioned 45 times, accounting for 22.6%. 3D laser scanners and photogrammetry equipment were used 22 times. In contrast, there are fewer articles that mention the use of touchable and interactive user interfaces, projection and mapping technology devices, photography and video capture devices, and we believe that there is still a lot of room for development in this field of devices (see Table 2).

Application refers to the application field after the project development mentioned in the paper. For example, Tsiviltidou’s article explores the case of using digital storytelling in the classroom to construct inquiry-based learning with digital museum collections, a project applied to classroom instruction and thus grouped under the type of application “Education and learning” (Tsiviltidou & Vavoula, 2023). According to the data analysis, we mainly extracted a total of 195 applications mentioned in the article, including education and learning, community and social participation, digitization and visualization research, virtual and AR technology applications, exhibition and museum experience enhancement, material and intangible cultural heritage protection and management, care for special groups, a total of 7 application fields. It is worth noting that 61 articles mentioned the field of exhibition and museum experience enhancement, accounting for 31.2%. There is a similar performance in the field of education and learning, accounting for 24.1%. It can be found that the application direction of the digital display of cultural heritage is still mainly to improve the basic function of user experience, while helping users better understand and learn the exhibition content, which is also the responsibility of museums. In addition, it is worth considering that there are relatively few applications in the field of community and social engagement, accounting for 9%. Therefore, we believe that in the process of digital display of cultural heritage, we should further open up the integration with the society and give play to the social functions of museums. In addition, the protection of cultural heritage and the care of special groups are the areas with the least attention, which also reflects the gap in the application of cultural heritage digitization in this field to a certain extent (see Table 3).

Technology refers to the technology used in the project development process mentioned in the paper. For example, Echavarria et al. described the presentation of different cultural heritage stories through interactive AR maps that use AR technology to enhance physical elements, which can be grouped under the category “Technologies for enhanced and immersive experiences” (Echavarria et al., 2022). According to the data analysis, we mainly extracted a total of 311 frequency of articles mentioning equipment in the article. It includes eight technology types: enhancement and immersion experience technology, interactive participation technology, social and community participation technology, content creation and management technology, data acquisition and analysis technology, information access and recommendation technology, physical and virtual interface integration technology, real-time computing and multimedia technology. Among them, the highest frequency of use is enhanced and immersive experience technology, up to 96 times, accounting for 30.9%. This kind of technology can be more inclined to meet the user’s sense of experience and create more emotional force in the same time and space, so it has been invested in more attention. In addition, social and community engagement, content creation and management, and data acquisition and analysis are three areas where considerable attention has been devoted (see Table 4).

Table 2. Categorization of devices mentioned in articles on immersive cultural heritage interaction experiences.

Device	Paper
AR	(Andrade & Dias, 2020; Arayaphan et al., 2022; Bergamasco et al., 2018; Bozzelli et al., 2019; Brancati et al., 2017; Carrozzino et al., 2011; Čejka et al., 2020; Ch'ng et al., 2019; Chen et al., 2013; Chiang et al., 2023; Comes et al., 2014; Damala et al., 2019; Echavarria et al., 2022; Gatelier et al., 2022; Hu, 2024; Jang & Kim, 2022; Krumpfen et al., 2021; Lassandro et al., 2021; Malik et al., 2021; Marcos, 2007; Neamțu et al., 2024; O'dwyer et al., 2021; Petrovič et al., 2021; Ridel et al., 2014; Sertalp et al., 2023; Stichelbaut et al., 2021; Szabo et al., 2017; Villa et al., 2017; Younes et al., 2016; Zhang et al., 2021; Zhu & Chung, 2024)
MR	(Bekele, 2019; Hammady et al., 2020; Jacobs & Loscos, 2006; Millard et al., 2020; Rahaman et al., 2019; Trunfio et al., 2023; Zaia et al., 2022)
VR	(Arayaphan et al., 2022; Argyriou et al., 2020; Bajaj & Bhattacharjee, 2024; Bergamasco et al., 2018; Bozzelli et al., 2019; Brumana et al., 2018; Bruno et al., 2010; Carrozzino et al., 2011; Ch'ng et al., 2019; Chen et al., 2013; Chen et al., 2010; Ferdani et al., 2020; Gatelier et al., 2022; Ghani et al., 2020; Han et al., 2020; Hu, 2024; Kersten et al., 2018; Krumpfen et al., 2021; Lassandro et al., 2021; Leow & Ch'ng, 2021; Loaiza Carvajal et al., 2020; Lu & Li, 2023; Lutz & Weintke, 1999; Malik et al., 2021; Mas et al., 2021; Monaco et al., 2022; Neamțu et al., 2024; Ocón, 2021; Petrelli & Roberts, 2023; Serain, 2018; Tong et al., 2023; Wu et al., 2022; Zhang et al., 2021; Zhao, 2023)
XR	(Neamțu et al., 2024; Zaia et al., 2022)
Mobile/PC/Laptop	(Aburamadan et al., 2022; Aigner, 2016; Andrade & Dias, 2020; Arayaphan et al., 2022; Arlitsch et al., 2003; Bartolini et al., 2016; Bergamasco et al., 2018; Bhaumik & Govil, 2020; Bruno et al., 2019; Bujari et al., 2017; Carletti, 2016; Carrozzino et al., 2011; Carrozzino et al., 2013; Čejka et al., 2020; Celentano & Dubois, 2017; Chen et al., 2022; Civantos et al., 2016; D'Albertis, 2018; Damala et al., 2019; Deng et al., 2019; Díaz et al., 2011; Dimoulas et al., 2014; Drygalska, 2024; Froschauer et al., 2013; Giaccardi & Palen, 2008; Gil-Melitón & Lerma, 2019; González Zardona et al., 2018; Grainger Clemson, 2014; Green et al., 2021; Gutierrez et al., 2007; Hess et al., 2016; Hulusic et al., 2023; Jaillot et al., 2020; Jiang et al., 2019; Jones et al., 2019; Kim et al., 2017; Konstantakis & Caridakis, 2020; Kuna et al., 2022; Kuroczyński, 2017; Lázaro et al., 2021; Leonov et al., 2015; Li & Kim, 2023; Li & Liew, 2015; Liew, 2014; Liritzis et al., 2015; Lužnik-Jancsary et al., 2020; Ma et al., 2023; Machidon et al., 2020; Marsili & Orlandi, 2020; Montusiewicz & Milosz, 2021; Neudecker & Tzadok, 2010; Noardo, 2018; Not et al., 2019; Permatasari et al., 2020; Peters et al., 2015; Petrelli & Roberts, 2023; Petrovič et al., 2021; Pietroni & Adami, 2014; Pistofidis et al., 2023; Portalés et al., 2021; Qi et al., 2023; Quattrini et al., 2020; Rattananungrot et al., 2024; Reerink, 2012; Renzi et al., 2023; Ricart et al., 2019; Rojas-Sola & Fuente, 2018; Scopigno et al., 2017; Semeraro et al., 2012; Simone et al., 2021; Smirnov et al., 2017; Smith & Iversen, 2014; Smith et al., 2018; Solima & Izzo, 2018; Spagnolo et al., 2021; Styliadis et al., 2009; Tai & Sung, 2019; Tsiviltidou & Vavoula, 2023; Villa et al., 2017; Viola, 2023; Vosinakis & Tsakonas, 2016; Vurpillot et al., 2019; Wu et al., 2022; Xiong, 2023; Zhao et al., 2020; Zhenrao et al., 2021; Zhou, 2020; Zhu & Chung, 2024)
None	(Adembri et al., 2018; Balzani et al., 2024; Cheng & Chou, 2022; Cheok et al., 2017; Croix et al., 2020; Deligiorgi et al., 2021; El-Hakim et al., 2004; Fan, 2024; García-Molina et al., 2021; Georgopoulos, 2014; Hong et al., 2017; Hou et al., 2022; Kamariotou et al., 2021; Katifori et al., 2020; Li & Ito, 2023; Li & Ito, 2021; Li et al., 2023; Liang et al., 2019; Mah et al., 2019; Menna & Nocerino, 2014; Nancarrow, 2020; Ocón, 2023; Psomadaki et al., 2019; Raheb et al., 2021; Smithies et al., 2022; Staropoli et al., 2023; Sutcliffe & Kim, 2014; Themistocleous, 2017; Vilbrandt et al., 2011; Wijnhoven & Moskvín, 2020; Wu, 2024; Xu et al., 2023; Xue et al., 2019; Yaagoubi et al., 2019; Yan et al., 2023; Yastikli, 2007; Zhu & Chung, 2024)

In the Sankey Diagram (see Figure 2), we pay attention to the sample correlation among the three categories so as to conduct a quality assessment of the application types and effects of important links in the digital display of cultural heritage, so as to identify the advantages and disadvantages therein. In this visual classification, we summarize the technologies of different devices in different application fields based on the hierarchical graph model. In it, similar technologies embodied by different devices are aggregated to form an application queue, which facilitates comparison between finding simpler or richer device usage logic in the run-up to the digital presentation or throughout the exhibition process. Specifically, node color represents the refined classification of different devices, applications, and technologies, node height represents the proportion of use of a given device, application, and technology, and the flow line between each pair of nodes represents the proportion of use to the type of the upper level. Based on this, we found that the use of traditional Mobile/PC/laptop terminals is still the largest, and they are widely used in almost all sample areas, especially to enhance the experience of exhibitions and museum (Gao et al., 2024). It is worth mentioning that the application of technology in the field of exhibitions and museums is also more concentrated and rich than in other fields. Among them, enhanced and immersive experience technologies contribute the most. In addition, VR devices and AR contribute similarly, but VR devices are more

widely used in education and learning. Unfortunately, the application of XR and MR has yet to be expanded, and the use of equipment for material and intangible heritage conservation and management, as well as community and social engagement, is also limited. In addition, we also noticed that the use of Mobile/PC/laptop side of the special population care application has not yet realized the corresponding technical connection.

4.2.2. Development trend analysis

In addition, we also counted the publication time of the sample. Considering that digitization and immersive presentation in the field of cultural heritage have undergone significant development over time—moving from initial exploratory phases to more mature, diverse applications—we have opted for a longer timeframe to capture this evolution. We aim to cover the early emergence of related research, the iterative technological advancements, the accumulation of practical applications, and the most recent rapid developments in the field. We found that the number of publications has been fluctuating at a low value from 1999 to 2013, which may be related to the low level of information technology development at that time. Since 2017, with the rapid improvement of information technology, the number of published articles has also begun to increase significantly, and the blowout growth will be formed in 2023, reaching 30

Table 3. Categorization of applications mentioned in articles on immersive cultural heritage interaction experiences.

Application	Paper
Education and Learning	(Arayaphan et al., 2022; Argyriou et al., 2020; Arlitsch et al., 2003; Bhaumik & Govil, 2020; Carletti, 2016; Carrozzino et al., 2013; Chen et al., 2013; Chen et al., 2010; Cheok et al., 2017; Civantos et al., 2016; El-Hakim et al., 2004; Green et al., 2021; Kim et al., 2017; Krumpfen et al., 2021; Lázaro et al., 2021; Leow & Ch'ng, 2021; Li & Ito, 2021; Lu & Li, 2023; Marsili & Orlandi, 2020; Mas et al., 2021; Menna & Nocerino, 2014; Neamțu et al., 2024; Pietroni & Adami, 2014; Psomadaki et al., 2019; Rattananarongrot et al., 2024; Reerink, 2012; Spagnolo et al., 2021; Styliadis et al., 2009; Sutcliffe & Kim, 2014; Szabo et al., 2017; Tsiviltidou & Vavoula, 2023; Villa et al., 2017; Vosinakis and Tsakonas, 2016; Wu et al., 2022; Zhao, 2023)
Community and Social Engagement	(Aigner, 2016; Carletti, 2016; Ch'ng et al., 2019; Chen et al., 2013; Chen et al., 2010; Chiang et al., 2023; D'Alberis, 2018; Echavarría et al., 2022; Ferdani et al., 2020; Fontanella et al., 2021; Froschauer et al., 2013; González Zarandona et al., 2018; Grainger Clemson, 2014; Jaillot et al., 2020; Jones et al., 2019; Katifori et al., 2020; Machidon et al., 2020; Marcos, 2007; Millard et al., 2020; Montusiewicz & Milosz, 2021; Neudecker & Tzadok, 2010; Noardo, 2018; Psomadaki et al., 2019; Rattananarongrot et al., 2024; Smithies et al., 2022)
Digitization and Visualization Research	(Adembri et al., 2018; Carrozzino et al., 2011; Ch'ng et al., 2019; Chen et al., 2022; Croix et al., 2020; Díaz et al., 2011; Drygalska, 2024; El-Hakim et al., 2004; Fan, 2024; Fontanella et al., 2021; Georgopoulos, 2014; Giaccardi & Palen, 2008; Gil-Melitón & Lerma, 2019; Jacobs & Loscos, 2006; Kuroczyński, 2017; Liang et al., 2019; Qi et al., 2023; Quattrini et al., 2020; Rahaman et al., 2019; Ricart et al., 2019; Rojas-Sola & Fuente, 2018; Serain, 2018; Smith et al., 2018; Spagnolo et al., 2021; Tai & Sung, 2019; Viola, 2023; Vurpillot et al., 2019; Xiong, 2023; Yastikli, 2007; Zhang et al., 2021; Zhu & Chung, 2024)
Exhibition and Museum Experience Enhanced	(Adembri et al., 2018; Aigner, 2016; Ardito et al., 2020; Arlitsch et al., 2003; Bajaj & Bhattacharjee, 2024; Bartolini et al., 2016; Bergamasco et al., 2018; Bruno et al., 2010; Bruno et al., 2019; Carletti, 2016; Carrozzino & Bergamasco, 2010; Celentano & Dubois, 2017; Civantos et al., 2016; D'Alberis, 2018; Drygalska, 2024; Georgopoulos, 2014; Ghani et al., 2020; Giaccardi & Palen, 2008; Gil-Melitón & Lerma, 2019; Gutierrez et al., 2007; Gutierrez et al., 2007; Hess et al., 2016; Jiang et al., 2019; Kamariotou et al., 2021; Lázaro et al., 2021; Leonov et al., 2015; Li & Ito, 2023; Li & Liew, 2015; Liew, 2014; Liritzis et al., 2015; Lutz & Weintke, 1999; Mah et al., 2019; Monaco et al., 2022; Neamțu et al., 2024; Noardo, 2018; Not et al., 2019; Ocón, 2021; Peters et al., 2015; Petrelli & Roberts, 2023; Portalés et al., 2021; Quattrini et al., 2020; Renzi et al., 2023; Rojas-Sola & Fuente, 2018; Scopigno et al., 2017; Serain, 2018; Simone et al., 2021; Smith & Iversen, 2014; Solima & Izzo, 2018; Styliadis et al., 2009; Tong et al., 2023; Villa et al., 2017; Wu, 2024; Yaagoubi et al., 2019; Zhao, 2023; Zhenrao et al., 2021; Zhou, 2020)
Management of (In)Tangible Cultural Heritage	(Aburamadan et al., 2022; Arayaphan et al., 2022; Balzani et al., 2024; Díaz et al., 2011; Dimoulas et al., 2014; García-Molina et al., 2021; Green et al., 2021; Han et al., 2020; Hess et al., 2016; Hou et al., 2022; Kuna et al., 2022; Li & Kim, 2023; Ma et al., 2023; Malik et al., 2021; Nancarrow, 2020; Permatasari et al., 2020; Raheb et al., 2021; Semeraro et al., 2012; Staropoli et al., 2023; Themistocleous, 2017; Vilbrandt et al., 2011; Xiong, 2023; Xue et al., 2019; Zhao et al., 2020)
Care for special peopled	(Pistofidis et al., 2023)
None	(Hong et al., 2017; Konstantakis & Caridakis, 2020; Suominen & Sivula, 2013; Wijnhoven & Moskvina, 2020)

articles. However, the number of published documents in 2020–2022 has dropped slightly, which we suspect may be related to the impact of the global novel coronavirus epidemic, and the development of relevant technologies is also limited. It is worth noting that the number of 2024 publications shown in the figure is less than 5, because we used the data up to January 2024 when compiling the data, so the 2024 data shown in the figure is not very valuable for reference. However, according to our trend forecast, the publication volume in the relevant field is likely to maintain significant growth in 2024 (see Figure 3).

5. Discussion

5.1. Strengths and benefits of immersive cultural heritage

Based on the analysis of the sample, we have sorted out and summarized the advantages of the equipment, applications and technologies. It is mainly divided into the following aspects: enlarging the sense of participation and experience, stimulating social attributes, promoting education and knowledge dissemination, optimizing the form of technological realization, and promoting heritage protection and dissemination. First, through the use of digital technologies and resources, a richer sensory experience can be obtained in an innovative narrative mode in the environment, deepening the memory of visitors for cultural heritage information (Liritzis et al., 2015). Personalized, real-time, present and entertaining digital display

tools can drive visitors to participate in the exhibition more actively (Buono et al., 2022).

Secondly, the equipment, technology and application of the digitization of cultural heritage can further stimulate the social character of the exhibition (Bautista, 2023). For example, in exhibition design, the combination of physical and digital can promote social interaction and community connection, thus promoting cultural transmission and cross-cultural communication, and realizing community co-creation. The use of social tags can make the digital system more accurately capture user interests and enrich user profiles (Oomen & Aroyo, 2011).

Third, in the field of education, digital intervention affects the whole process of knowledge dissemination (Ott & Pozzi, 2011). In the lead-up period, digital technologies, devices and applications can provide rich learning resources and make them easier to access and discover (Jang & Kim, 2022). In the process of knowledge transmission, because of the vividness and individuation of the educational experience, the autonomy and efficiency of learning are greatly improved (Semeraro et al., 2012). In addition, in terms of the cultivation of learning thinking, digitization presents a more diverse and fluid knowledge form, helping learners to cultivate a more comprehensive thinking mode, interdisciplinary thinking ability, critical analysis ability, and deep-seated aesthetic experience, thus producing more creative and forward-looking expressions (Kuroczyński, 2017).

Fourthly, in terms of technology implementation, logical digital methods, clearer visual expression, wide accessibility,

Table 4. Categorization of technology mentioned in articles on immersive cultural heritage interaction experiences.

Application	Paper
Enhanced and Immersive Experience	(Aigner, 2016; Argyriou et al., 2020; Arlitsch et al., 2003; Bruno et al., 2010; Bruno et al., 2019; Carrozzino & Bergamasco, 2010; Carrozzino et al., 2013; Deligiorgi et al., 2021; El-Hakim et al., 2004; Giaccardi & Palen, 2008; Grainger Clemson, 2014; Gutierrez et al., 2007; Jiang et al., 2019; Kamariotou et al., 2021; Kim et al., 2017; Kuroczyński, 2017; Leonov et al., 2015; Li & Ito, 2023; Li & Ito, 2021; Lutz & Weintke, 1999; Menna & Nocerino, 2014; Scopigno et al., 2017; Simone et al., 2021; Staropoli et al., 2023; Styliadis et al., 2009; Xiong, 2023)
Interaction and Participation	(Bajaj & Bhattacharjee, 2024; Bozzelli et al., 2019; Carrozzino et al., 2011; Cheok et al., 2017; Damala et al., 2019; Drygalska, 2024; Ferdani et al., 2020; Han et al., 2020; Hess et al., 2016; Hou et al., 2022; Leonov et al., 2015; Leow & Ch'ng, 2021; Li & Liew, 2015; Ma et al., 2023; Mah et al., 2019; Psomadaki et al., 2019; Raheb et al., 2021; Smith & Iversen, 2014; Sutcliffe & Kim, 2014; Viola, 2023; Wu et al., 2022; Zhao et al., 2020)
Social and Community Engagement	(Bozzelli et al., 2019; Bujari et al., 2017; Carletti, 2016; Chen et al., 2013; Chen et al., 2010; Damala et al., 2019; Fontanella et al., 2021; Froschauer et al., 2013; Kuroczyński, 2017; Leonov et al., 2015; Neudecker & Tzadok, 2010; Psomadaki et al., 2019; Rahaman et al., 2019; Rattananungrot et al., 2024; Semeraro et al., 2012; Smith & Iversen, 2014; Suominen & Sivula, 2013; Vurpillot et al., 2019; Wu et al., 2022)
Content Creation and Management	(Arayaphan et al., 2022; Bhaumik & Govil, 2020; Bozzelli et al., 2019; Brumana et al., 2018; Chen et al., 2022; D'Albertis, 2018; Damala et al., 2019; Díaz et al., 2011; Dimoulas et al., 2014; González Zarandona et al., 2018; Hou et al., 2022; Hulusic et al., 2023; Kamariotou et al., 2021; Katifori et al., 2020; Kuna et al., 2022; Leonov et al., 2015; Leow & Ch'ng, 2021; Li et al., 2023; Liew, 2014; Ma et al., 2023; Marcos, 2007; Marsili & Orlandi, 2020; Menna & Nocerino, 2014; Ocón, 2021; Ocón, 2023; Pietroni & Adami, 2014; Psomadaki et al., 2019; Qi et al., 2023; Reerink, 2012; Sertalp et al., 2023; Simone et al., 2021; Smith & Iversen, 2014; Smithies et al., 2022; Stichelbaut et al., 2021; Styliadis et al., 2009; Szabo et al., 2017; Tsiviltidou & Vavoula, 2023; Xiong, 2023; Yan et al., 2023)
Data Acquisition and Analysis	(Adembri et al., 2018; Ch'ng et al., 2019; Comes et al., 2014; Fontanella et al., 2021; García-Molina et al., 2021; Georgopoulos, 2014; Gil-Melitón & Lerma, 2019; Hess et al., 2016; Kuroczyński, 2017; Lázaro et al., 2021; Leonov et al., 2015; Liang et al., 2019; Liritzis et al., 2015; Lužnik-Jancsary et al., 2020; Mas et al., 2021; Menna & Nocerino, 2014; Ocón, 2021; Pietroni & Adami, 2014; Pistofidis et al., 2023; Quattrini et al., 2020; Rahaman et al., 2019; Rojas-Sola & Fuente, 2018; Spagnolo et al., 2021; Styliadis et al., 2009; Tai & Sung, 2019; Themistocleous, 2017; Wu et al., 2022; Yaagoubi et al., 2019; Yastikli, 2007)
Information Access and Recommendations	(Arayaphan et al., 2022; Cheok et al., 2017; Fan, 2024; Giaccardi & Palen, 2008; Kuroczyński, 2017; Leonov et al., 2015; Li et al., 2023; Machidon et al., 2020; Noardo, 2018; Permatasari et al., 2020; Serain, 2018; Simone et al., 2021; Vosinakis and Tsakonas, 2016; Xu et al., 2023)
Physical and Virtual Interface Integration	(Ardito et al., 2020; Brancati et al., 2017; Krumpfen et al., 2021; Liritzis et al., 2015; Malik et al., 2021; Montusiewicz & Milosz, 2021; Neamtu et al., 2024; Not et al., 2019; Ocón, 2021; Pistofidis et al., 2023; Simone et al., 2021; Vilbrandt et al., 2011; Villa et al., 2017; Zhenrao et al., 2021)
Real-time Computing and Multimedia	(Anastasovitis & Roumeliotis, 2020; Bartolini et al., 2016; Bergamasco et al., 2018; Celentano & Dubois, 2017; Chen et al., 2013; Civantos et al., 2016; Drygalska, 2024; Jaillot et al., 2020; Marsili & Orlandi, 2020; Ocón, 2023; Quattrini et al., 2020; Renzi et al., 2023; Smirnov et al., 2017; Wu, 2024; Zhao, 2023)
None	(Aburamadan et al., 2022; Cheng & Chou, 2022; Deng et al., 2019; Hong et al., 2017; Jones et al., 2019; Konstantakis & Caridakis, 2020; Li & Kim, 2023; Ricart et al., 2019; Solima & Izzo, 2018; Xue et al., 2019; Zhou, 2020; Zhu & Chung, 2024)

research efficiency and accurate implementation reduce the technical threshold to a certain extent, improve the technical acceptance of non-professionals, and provide an easy-to-accept learning tool for the dissemination of cultural heritage (Younes et al., 2016). On one level, digital technology is cheaper and easier to implement than traditional forms of exhibition.

Fifth, in terms of the protection and dissemination of cultural heritage, digital technology, equipment, and applications create more opportunities for the discovery of details, ensure the integrity and accuracy of data, and enhance the visualization of cultural heritage details to provide more powerful support for the cultural heritage itself (Yastikli, 2007). In addition, digital tools have opened up new possibilities when visiting cultural heritage, helping to reduce risks, improve accessibility and make it more humane (Liritzis et al., 2015).

In general, digital technologies and applications have brought unprecedented advantages to the exhibition, dissemination and conservation of cultural heritage. These technologies not only enhance the sensory experience and social interaction of participants but also promote the dissemination of knowledge and the development of education through innovative ways. At the same time, digital technology has lowered the technical threshold of cultural heritage protection, promoted broader audience participation, and provided strong support for the inheritance and

development of cultural heritage. Through these technological means, cultural heritage can be more widely disseminated while being protected, enhancing the possibility of cross-cultural communication, and further promoting cultural diversity and global understanding.

5.2. Challenges and limitations in immersive cultural heritage

We have also sorted out and summarized the shortcomings of the equipment, applications and technologies. Mainly divided into the following aspects: technical barriers, sustainability, experience, and safety. First, technical understanding and operational difficulties may hinder initial users and special groups such as children and the elderly, affecting the access experience. In addition, high digitalization and excessive technological dependence make cultural heritage dependent on specific hardware and software platforms, which can lead to technical failures and compatibility issues (Król & Hernik, 2006).

Secondly, sustainability issues are first reflected in terms of duration, technology and financial investment, which may be applied to the wider field of cultural heritage display (Borin & Donato, 2023). In addition, users are unstable, changing participation, diverse cultural and political differences, and personalized dynamic needs mean that the digital

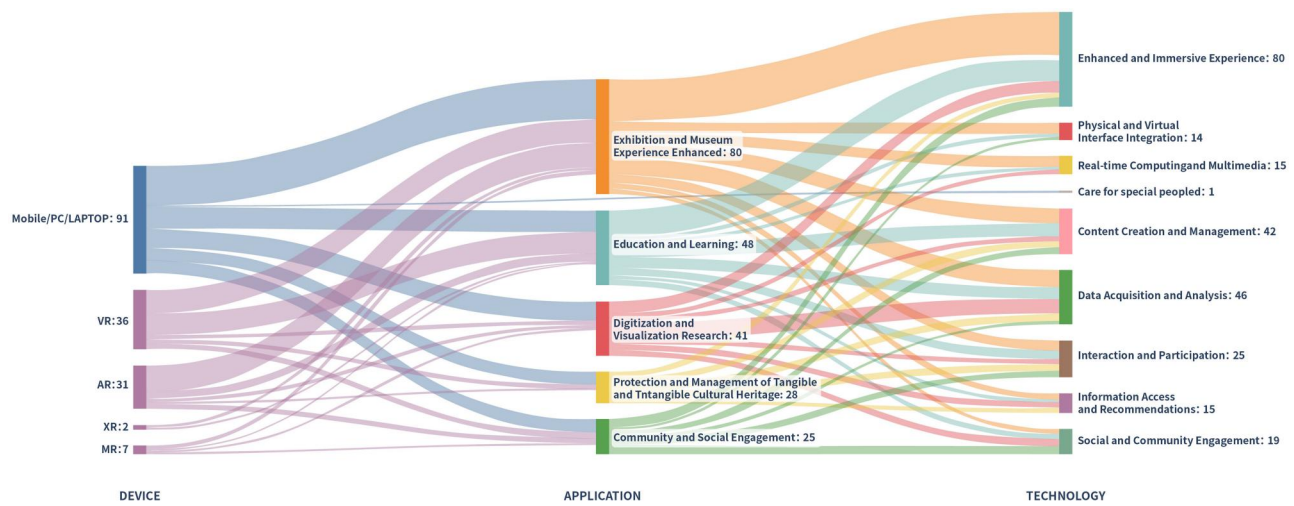


Figure 2. Sankey diagram of device, application and technology.

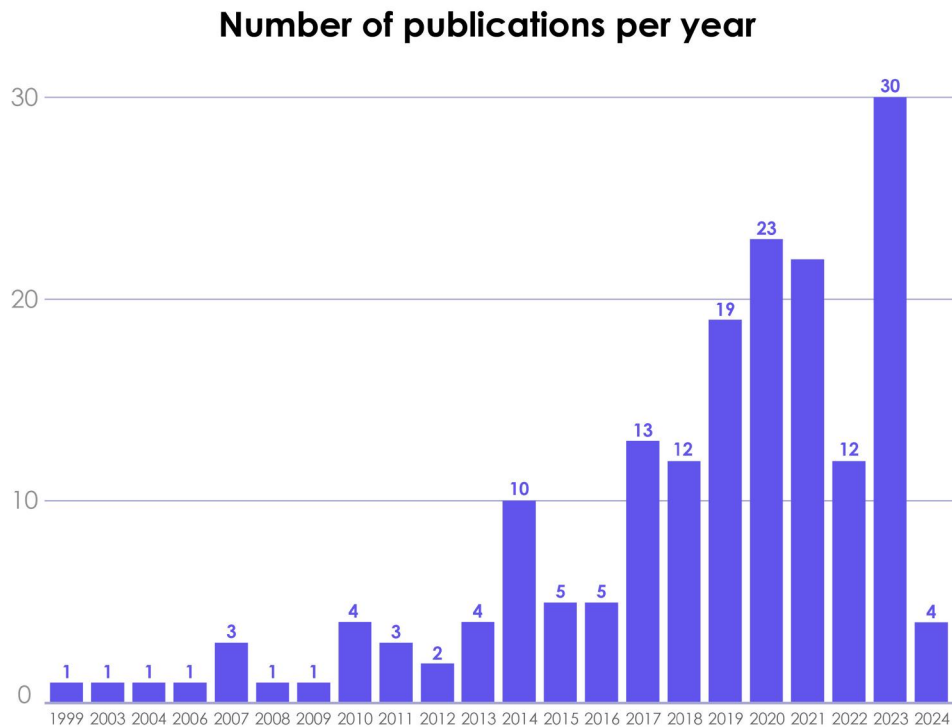


Figure 3. Chart of trends in the number of articles published in the field (1999–2024).

application of cultural heritage needs more long-term and stable support (Borin & Donato, 2023).

Third, the audience's sense of experience will be affected by information overload, and the huge amount of information will make some experience groups feel at a loss. What is more obvious is that the full application of digitalization will lead to the limitation of cultural authenticity and physical experience, and it is difficult to fully convey the cultural background and deep meaning of some traditional crafts, resulting in defects in audience understanding (Corona, 2023). Maintaining a balance between virtual content and the real world environment can be a challenge, and too many virtual elements can also distract visitors (Newell, 2012).

Fourth, security issues are reflected in the protection of cultural heritage and copyright issues, user personal data privacy

and security issues (Manžuch, 2017). In addition, for some users, the VR experience may cause motion sickness effects and reduce the quality of the experience (Chattha et al., 2020).

Overall, while digital technologies bring significant advantages to the display and preservation of cultural heritage, there are still some challenges and limitations that need to be addressed. The complexity and platform dependence of technical operations may limit the participation of some groups, and technical failures and compatibility issues are unavoidable. The sustainability of digital applications is also under long-term pressure from changes in funding, technology and user needs. In addition, information overload, the weakening of cultural authenticity, and the replacement of physical perception by virtual experiences may affect the audience's deep cultural understanding. Security issues can

not be ignored, involving the protection of cultural copyright and user privacy (Mulumba et al., 2017). While promoting the digitization of cultural heritage, we must actively address these issues to ensure its long-term stable and healthy development.

5.3. Gaps and risks in current immersive cultural heritage practices

We also found some areas that have not been fully explored in the research, and these missing parts may have an important impact on the digital display and dissemination of cultural heritage. It is manifested in the misinterpretation of cultural heritage, the influence of purity in media experience, and the potential damage of cultural heritage.

5.3.1. Overinterpretation or misinterpretation of cultural heritage in immersive representations

Digital immersion in the presentation of cultural heritage can sometimes lead to over-interpretation or misunderstanding, thus deviating from the original intention of technical intervention (Muir, 2009). For example, one of the purposes of digital artefacts is to deepen the understanding and appreciation of real artefacts. When the focus is no longer on content but on technology, it may not be easy to use and distract visitors from the cultural heritage, leading to technological bias (Havemann et al., 2008).

In addition, 3D reconstruction techniques have been implemented in many significant research projects for digital cultural heritage (Colombo et al., 2005; Keep, 2022); however, these techniques sometimes rely excessively on imagination and/or visual additions (Gomes et al., 2014; Han et al., 2021). Spatiotemporal discrepancies, contextual detachment of real data, and technical errors in digital databases can further distort public understanding and compromise authenticity (Colombo et al., 2005).

5.3.2. The impact on “purity in media experience”

The overuse of digital technology may compromise the “purity in media experience” in the display of cultural heritage (Laskowska & Marcyński, 2016). The excessive use of technology may cause the original cultural details of the cultural heritage to be lost and the deep meaning to be tampered with or ignored, resulting in the cultural interpretation and historical background being covered up by the technical display, deviating from the essence of the exhibition. From the audience level, if there are too many digital elements and interactive content, the too rich sensory experience will make it difficult for the audience to concentrate on the exhibition, interfere with the audience’s reception of the exhibition content information and in-depth thinking process so that the cultural heritage exhibition will be confined to the technical display level (Havemann et al., 2008).

5.3.3. Potential damage to cultural heritage from immersive practices

Digital display technologies can also pose risks to cultural heritage. Light and noise pollution, along with excessive visitor interaction, can cause physical damage (Méndez et al., 2022). At the same time, it is also necessary to consider the indirect effects of light on cultural heritage sites, such as the harm caused by the attraction of phototaxis (Verovnik et al., 2015). Inappropriate light can affect the creation of emotions as well as suggest, evoke and support the visitor experience (Di Salvo, 2014). One example is the night tour at the Longmen Grottoes in Luoyang, China (Liu et al., 2012). Field research revealed that the tour was initially suspended after experts warned that the lights attracted insects, which in turn drew animals whose droppings damaged the cave structures (Liu et al., 2012). The tour resumed after replacing the light source based on expert advice (Li & Hua, 2024). This case shows that the impact of light shows varies depending on the materials of the heritage site, highlighting the need for tailored protection measures (Bista et al., 2021). Similarly, a light show at the Great Wall was halted due to public and expert opposition, for reasons that we do not know, but may have been largely due to concerns that the site was over-commercialized, compromising its conservation, or including excessive brightness, glare, uneven light distribution, inappropriate color temperature, poor color rendering index, as well as resulting in excessive lighting, light clutter, and light intrusion (Bista et al., 2021; Zielinska-Dabkowska & Xavia, 2018). These cases illustrate the delicate balance between cultural heritage preservation and public display.

5.3.4. Other issues in immersive cultural heritage practices

In addition to the previously mentioned risks, several other challenges have surfaced in the application of immersive technologies in cultural heritage preservation and exhibition. These challenges are associated with ethical concerns, economic disparity, and technological standardization, each of which warrants deeper investigation and consideration.

One notable issue is the ethical dilemma associated with the virtual reproduction of sensitive cultural sites. When sacred Spaces or emotionally charged historical events are portrayed in virtual form, people may worry about the trivialization or commodification of cultural experiences. Sites such as war or disaster memorials are critical to the sensitivity of cultural and historical contexts (Arthur, 2014). The line between educational engagement and the commercialization of tragedy or sacred heritage is often blurred, leading to potential ethical violations (Drakakis, 2020). Another important aspect is that when Western frameworks are used for immersive exhibition and Virtual Representation of indigenous knowledge, this can distort its cultural integrity, hence the need for a more inclusive and participatory approach (Manžuch, 2017).

The rapid adoption of immersive technologies in cultural heritage has also raised concerns about economic inequality (Franks, 2017). Many cultural institutions, especially those in developing regions, may lack the funds or resources to

integrate advanced technologies into their exhibitions (Franks, 2017). This has created a growing gap between well-funded museums and smaller institutions or sites that rely on traditional methods of preservation and exhibition (Franks, 2017). In addition, visitors from disadvantaged economic backgrounds may not have access to expensive VR or AR headsets, which may prevent them from having a full range of cultural experiences (Franks, 2017). Thus, access to the democratization of immersive cultural heritage experiences remains an unsolved challenge (Franks, 2017).

Another concern is the lack of standardization in the development and application of technologies for immersive experiences. Different institutions often adopt proprietary technologies, leading to compatibility and interoperability issues between digital platforms (Apeldoorn & Volkers, 2024). This fragmentation can hinder the seamless sharing and preservation of digital cultural heritage across borders, as well as the long-term sustainability of digital archives (Hamad & Jia, 2022). Without universally accepted standards, organizations may face challenges maintaining or upgrading immersive installations, especially as technology evolves.

While immersive experiences offer new ways to interact with cultural heritage, they also have the potential to disconnect viewers from the material and tactile quality of physical artifacts. The ability to touch, feel, or closely examine the texture and craftsmanship of objects is often necessary for the full appreciation of cultural heritage (Feng et al., 2022). Immersive technologies can simulate these qualities to a certain extent, but the loss of materiality can distance visitors from the physical reality of heritage, reduce their sensory engagement, and may lead to a superficial understanding of cultural artifacts.

These issues highlight the complexity and risks of using immersive technologies in cultural heritage. While there are many benefits, these emerging challenges must be addressed to ensure that immersive cultural heritage practices remain respectful, inclusive and sustainable.

6. Conclusion and future work

In this paper we have provided a comprehensive review of the application of immersive technologies in cultural heritage, identifying key opportunities, challenges, and gaps in the field. Analyzing over 5,000 articles, we distilled insights from 177 key papers to map the current landscape of immersive technologies, including VR, AR, and MR, and their use in cultural heritage. Our findings highlighted the transformative impact of these technologies in enhancing preservation, education, and cultural dissemination, offering personalized, interactive experiences that deepen audience engagement and promote cross-cultural dialogue.

However, grand challenges remained, including technical barriers such as platform dependence and interoperability, sustainability concerns, and risks of diminishing cultural authenticity through digital reconstructions. *Data privacy* and *misrepresentation of cultural heritage* are critical considerations that must be addressed alongside other ethical issues. Ensuring responsible use of these technologies

requires a balanced approach that respects both the technical and ethical dimensions. Furthermore, addressing these areas necessitates ongoing research to ensure that the development of digital and immersive display technologies honors the essence of cultural heritage and aligns with societal expectations.

Future research should focus on addressing these challenges through sustainable, scalable solutions, balancing innovation with cultural authenticity, and fostering collaborations between cultural heritage experts and technologists. Additionally, greater awareness of the ethical and social implications of these technologies is needed, especially in regard to cultural representation and intangible heritage. By overcoming these challenges, immersive technologies can reshape how we engage with cultural heritage, creating more inclusive and globally accessible experiences. Our findings offer a roadmap for future research and practice in this evolving field.

We also plan to organize a workshop with practitioners in cultural heritage, as well as experts in VR/AR and immersive interactive technologies, to exchange ideas on creating more inclusive and engaging experiences for users. We aim to collaborate with governments and relevant institutions (for example, museums) to develop more comprehensive cultural heritage experiences, including advanced equipment and dedicated venues.

Note

1. <https://whc.unesco.org/en/conventiontext>.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported in part by a grant from Research Project of the National Museum: "Research on Intelligent Interactive Design for Museum Exhibitions Based on Audience Experience" [# GBKX2021Z10].

ORCID

Hanbing Wang  <http://orcid.org/0009-0008-4449-9444>
 Junyan Du  <http://orcid.org/0009-0008-8951-1910>
 Yue Li  <http://orcid.org/0000-0003-3728-218X>
 Lie Zhang  <http://orcid.org/0009-0009-6496-9885>
 Xiang Li  <http://orcid.org/0000-0001-5529-071X>

Data availability statement

All literature analyzed during this project is at <https://www.repository.cam.ac.uk/handle/1810/379779> (Wang et al., 2025).

References

- Aburamadan, R., Trillo, C., Cotella, V. A., Di Perna, E., Ncube, C., Moustaka, A., Udeaja, C., & Awuah, K. G. B. (2022). Developing a heritage BIM shared library for two case studies in Jordan's heritage: The house of art in Amman and the Qaqish house in the world

- heritage city of as-salt. *Heritage Science*, 10(1), 836. <https://doi.org/10.1186/s40494-022-00836-w>
- Adembri, B., Cipriani, L., & Bertacchi, G. (2018). Virtual anastylosis applied to the architectural decoration of mixtilinear buildings in Villa Adriana: The case study of the scattered friezes of the teatro marittimo. *Applied Geomatics*, 10(4), 279–293. <https://doi.org/10.1007/s12518-018-0207-5>
- Aigner, A. (2016). Heritage-making from below: The politics of exhibiting architectural heritage on the internet—a case study. *International Journal of Heritage Studies*, 22(3), 181–199. <https://doi.org/10.1080/13527258.2015.1107615>
- Anastasovitis, E., & Roumeliotis, M. (2020). Creative industries and immersive technologies for training, understanding and communication in cultural heritage. In *Euro-Mediterranean Conference* (pp. 450–461). Springer. https://doi.org/10.1007/978-3-030-73043-7_37
- Andrade, J. G., & Dias, P. (2020). A phygital approach to cultural heritage: Augmented reality at regaleira. *Virtual Archaeology Review*, 11(22), 15–25. <https://doi.org/10.4995/var.2020.11663>
- Apeldoorn, N., & Volkers, N. (2024). *Immersive experience gap report* [Technical report]. Breda University.
- Arayaphan, W., Intawong, K., & Puritat, K. (2022). Digitalization of ancient fabric using virtual reality technology at the wieng yong house museum: The FabricVR project. *Digital Applications in Archaeology and Cultural Heritage*, 26, e00233. <https://doi.org/10.1108/EL-09-2021-0171>
- Ardito, C., Desolda, G., Lanzilotti, R., Malizia, A., Matera, M., Buono, P., & Piccinno, A. (2020). User-defined semantics for the design of IoT systems enabling smart interactive experiences. *Personal and Ubiquitous Computing*, 24(6), 781–796. <https://doi.org/10.1007/s00779-020-01457-5>
- Argyriou, L., Economou, D., & Bouki, V. (2020). Design methodology for 360° immersive video applications: The case study of a cultural heritage virtual tour. *Personal and Ubiquitous Computing*, 24(6), 843–859. <https://doi.org/10.1007/s00779-020-01373-8>
- Arlitsch, K., Yapp, L., & Edge, K. (2003). The Utah digital newspapers project. *D-Lib Magazine*, 9(3). <https://doi.org/10.1045/march2003-arlitsch>
- Arthur, P. (2014). Memory and commemoration in the digital present. In *Contemporary approaches in literary trauma theory* (pp. 152–175). Springer. https://doi.org/10.1057/9781137365941_7
- Bajaj, A. J., & Bhattacharjee, A. (2024). *Design and development of digital humans in virtual exhibition space*. Springer. <https://doi.org/10.1007/s11042-023-17100-3>
- Balzani, R., Barzaghi, S., Bitelli, G., Bonifazi, F., Bordignon, A., Cipriani, L., Colitti, S., Collina, F., Daquino, M., Fabbri, F., Fanini, B., Fantini, F., Ferdani, D., Fiorini, G., Formia, E., Forte, A., Giacomini, F., Girelli, V. A., Gualandi, B., ... Vittuari, L. (2024). Saving temporary exhibitions in virtual environments: The digital renaissance of ulisse aldrovandi – acquisition and digitisation of cultural heritage objects. *Digital Applications in Archaeology and Cultural Heritage*, 32, e00309. <https://doi.org/10.1016/j.daach.2023.e00309>
- Baratin, L., Gasparetto, F., & Tronconi, V. (2023). What communication about heritage conservation a challenge for digital documentation content. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-M-2-2023, 183–194. <https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-183-2023>
- Bartolini, I., Moscato, V., Pensa, R. G., Penta, A., Picariello, A., Sansone, C., & Sapino, M. L. (2016). Recommending multimedia visiting paths in cultural heritage applications. *Multimedia Tools and Applications*, 75(7), 3813–3842. <https://doi.org/10.1007/s11042-014-2062-7>
- Bautista, S. S. (2023). Museums in the digital age: Changing meanings of place, community, and culture. In *The international archives of the photogrammetry, remote sensing and spatial information sciences* (Vol. XLVIII-M-2-2023, pp. 183–194), Rowman & Littlefield.
- Bekele, M. K. (2019). Walkable mixed reality map as interaction interface for virtual heritage. *Digital Applications in Archaeology and Cultural Heritage*, 15, e00127. <https://doi.org/10.1016/j.daach.2019.e00127>
- 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), 1–36. <https://doi.org/10.1145/3145534>
- Bentley, S. V., Naughtin, C. K., McGrath, M. J., Irons, J. L., & Cooper, P. S. (2024). The digital divide in action: How experiences of digital technology shape future relationships with artificial intelligence. *AI and Ethics*, 4(4), 901–915. <https://doi.org/10.1007/s43681-024-00452-3>
- Beraldin, J.-A., Picard, M., El-Hakim, S., Godin, G., Borgeat, L., Blais, F., Paquet, E., Rioux, M., Valzano, V., & Bandiera, A. (2005). *Virtual reconstruction of heritage sites: Opportunities and challenges created by 3d technologies* [Paper presentation]. The International Workshop on Recording, Modeling and Visualization of Cultural Heritage, Ascona, Switzerland.
- Bergamasco, M., Falvo, P. G., & Manera, G. V. (2018). Perceiving cultural heritage. *Studies in Digital Heritage*, 2(1), II–IV. <https://doi.org/10.14434/sdh.v2i1.27979>
- Bhaumik, G., & Govil, M. C. (2020). Conserving thangka - a technical approach unto the preservation of Buddhist Thangka through automation. *Digital Applications in Archaeology and Cultural Heritage*, 18, e00149. <https://doi.org/10.1016/j.daach.2020.e00149>
- Bista, D., Bista, A., Shrestha, A., Doulos, L. T., Bhusal, P., Zissis, G., Topalis, F., & Chhetri, B. B. (2021). Lighting for cultural and heritage site: An innovative approach for lighting in the distinct pagoda-style architecture of Nepal. *Sustainability*, 13(5), 2720. <https://doi.org/10.3390/su13052720>
- Boboc, R. G., Băutu, E., Gîrbacia, F., Popovici, N., & Popovici, D.-M. (2022). Augmented reality in cultural heritage: An overview of the last decade of applications. *Applied Sciences*, 12(19), 9859. <https://doi.org/10.3390/app12199859>
- Borin, E., & Donato, F. (2023). Financial sustainability of digitizing cultural heritage: The international platform europeana. *Journal of Risk and Financial Management*, 16(10), 421. <https://doi.org/10.3390/jrfm16100421>
- 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 ArkæVision project. *Digital Applications in Archaeology and Cultural Heritage*, 15, e00124. <https://doi.org/10.1016/j.daach.2019.e00124>
- Brancati, N., Caggianese, G., Frucci, M., Gallo, L., & Neroni, P. (2017). Experiencing touchless interaction with augmented content on wearable head-mounted displays in cultural heritage applications. *Personal and Ubiquitous Computing*, 21(2), 203–217. <https://doi.org/10.1007/s00779-016-0987-8>
- Brumana, R., Oreni, D., Caspani, S., & Previtali, M. (2018). Virtual museums and built environment: Narratives and immersive experience via multi-temporal geodata hub. *Virtual Archaeology Review*, 9(19), 34–49. <https://doi.org/10.4995/var.2018.9918>
- Bruno, F., Barbieri, L., Muzzupappa, M., Tusa, S., Fresina, A., Oliveri, F., Lagudi, A., Cozza, A., & Peluso, R. (2019). Enhancing learning and access to underwater cultural heritage through digital technologies: The case study of the “cala minnola” shipwreck site. *Digital Applications in Archaeology and Cultural Heritage*, 13, e00103. <https://doi.org/10.1016/j.daach.2019.e00103>
- Bruno, F., Bruno, S., De Sensi, G., Luchi, M.-L., Mancuso, S., & Muzzupappa, M. (2010). From 3D reconstruction to virtual reality: A complete methodology for digital archaeological exhibition. *Journal of Cultural Heritage*, 11(1), 42–49. <https://doi.org/10.1016/j.culher.2009.02.006>
- Bujari, A., Ciman, M., Gaggi, O., & Palazzi, C. E. (2017). Using gamification to discover cultural heritage locations from geo-tagged photos. *Personal and Ubiquitous Computing*, 21(2), 235–252. <https://doi.org/10.1007/s00779-016-0989-6>
- Buono, M., Capece, S., Chivăran, C., Gerbino, S., Giugliano, G., Greco, A., Laudante, E., Nappi, M. L., & Scognamiglio, C. (2022). Multisensory fruition between cultural heritage and digital transformation. In *Perspectives on Design and Digital Communication III*

- (pp. 329–355). Springer International Publishing. https://doi.org/10.1007/978-3-031-06809-6_21
- Buragohain, D., Meng, Y., Deng, C., Li, Q., & Chaudhary, S. (2024). Digitalizing cultural heritage through metaverse applications: Challenges, opportunities, and strategies. *Heritage Science*, 12(1), 295. <https://doi.org/10.1186/s40494-024-01403-1>
- Carletti, L. (2016). Participatory heritage: Scaffolding citizen scholarship. *International Information & Library Review*, 48(3), 196–203. <https://doi.org/10.1080/10572317.2016.1205367>
- Carrozzino, M., & Bergamasco, M. (2010). Beyond virtual museums: Experiencing immersive virtual reality in real museums. *Journal of Cultural Heritage*, 11(4), 452–458. <https://doi.org/10.1016/j.culher.2010.04.001>
- Carrozzino, M., Bruno, N., & Bergamasco, M. (2013). Designing interaction metaphors for web3d cultural dissemination. *Journal of Cultural Heritage*, 14(2), 146–155. <https://doi.org/10.1016/j.culher.2012.01.009>
- Carrozzino, M., Scucces, A., Leonardi, R., Evangelista, C., & Bergamasco, M. (2011). Virtually preserving the intangible heritage of artistic handicraft. *Journal of Cultural Heritage*, 12(1), 82–87. <https://doi.org/10.1016/j.culher.2010.10.002>
- Čejka, J., Zsíros, A., & Liarokapis, F. (2020). A hybrid augmented reality guide for underwater cultural heritage sites. *Personal and Ubiquitous Computing*, 24(6), 815–828. <https://doi.org/10.1007/s00779-019-01354-6>
- Celentano, A., & Dubois, E. (2017). A layered structure for a design space dedicated to rich interactive multimedia content. *Multimedia Tools and Applications*, 76(4), 5191–5220. <https://doi.org/10.1007/s11042-016-3714-6>
- Ch'ng, E., Cai, S., Zhang, T. E., & Leow, F.-T. (2019). Crowdsourcing 3D cultural heritage: Best practice for mass photogrammetry. *Journal of Cultural Heritage Management and Sustainable Development*, 9(1), 24–42. <https://doi.org/10.1108/JCHMSD-03-2018-0018>
- Chattha, U. A., Janjua, U. I., Anwar, F., Madni, T. M., Cheema, M. F., & Janjua, S. I. (2020). Motion sickness in virtual reality: An empirical evaluation. *IEEE Access*, 8, 130486–130499. <https://doi.org/10.1109/ACCESS.2020.3007076>
- Chen, C.-M., Ling, T.-S., Chang, C., Hsu, C.-F., & Lim, C.-P. (2022). Development and application of a digital humanities research platform for biographies of Malaysian personalities. *The Electronic Library*, 40(4), 313–337. <https://doi.org/10.1108/EL-01-2022-0007>
- Chen, S., Pan, Z., Zhang, M., & Shen, H. (2013). A case study of user immersion-based systematic design for serious heritage games. *Multimedia Tools and Applications*, 62(3), 633–658. <https://doi.org/10.1007/s11042-011-0864-4>
- Chen, W., Zhang, M., Pan, Z., Liu, G., Shen, H., Chen, S., & Liu, Y. (2010). Animations, games, and virtual reality for the Jing-Hang grand canal. *IEEE Computer Graphics and Applications*, 30(3), 84–88. <https://doi.org/10.1109/MCG.2010.49>
- Cheng, Y.-J., & Chou, S.-L. (2022). Using digital humanity approaches to visualize and evaluate the cultural heritage ontology. *The Electronic Library*, 40(1/2), 83–98. <https://doi.org/10.1108/EL-09-2021-0171>
- Cheok, A. D., Edirisinghe, C., & Karunanayaka, K. (2017). Confucius computer: A philosophical digital agent for intergenerational philosophical play. *Personal and Ubiquitous Computing*, 21(2), 327–343. <https://doi.org/10.1007/s00779-016-0995-8>
- Chiang, K.-C., Weng, C., Rathinasabapathi, A., Chen, H., & Su, J.-H. (2023). Augmented reality supported learning for cultural heritage of Taiwan in on-site and off-site environments: The case of a Daxi Old Street. *Journal on Computing and Cultural Heritage*, 16(3), 1–17. <https://doi.org/10.1145/3589231>
- Chong, H. T., Lim, C. K., Ahmed, M. F., Tan, K. L., & Mokhtar, M. B. (2021). Virtual reality usability and accessibility for cultural heritage practices: Challenges mapping and recommendations. *Electronics*, 10(12), 1430. <https://doi.org/10.3390/electronics10121430>
- Civantos, A. M., Brown, M., Coughlan, T., Ainsworth, S., & Lorenz, K. (2016). Using mobile media creation to structure museum interpretation with professional vision. *Personal and Ubiquitous Computing*, 20(1), 23–36. <https://doi.org/10.1007/s00779-015-0895-3>
- Colombo, C., Del Bimbo, A., & Pernici, F. (2005). Metric 3D reconstruction and texture acquisition of surfaces of revolution from a single uncalibrated view. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 27(1), 99–114. <https://doi.org/10.1109/TPAMI.2005.14>
- Comes, R., Neamțu, C., Buna, Z., Badiu, I., & Pupeză, P. (2014). Methodology to create 3d models for augmented reality applications using scanned point clouds. *Mediterranean Archaeology and Archaeometry*, 14(4), 35–44. <https://doi.org/10.5281/zenodo.13703>
- Corona, L. (2023). Digitization: An overview of the advantages and disadvantages. In *Aspects of digital libraries - digitization, standards, open access, repositories and user's skills*. IntechOpen. <https://doi.org/10.5772/intechopen.1002006>
- Croix, S., Deckers, P., & Sindbæk, S. M. (2020). Recasting a Viking warrior woman from ribe: 3D digital image reconstruction compared. *Journal of Archaeological Science: Reports*, 32, 102455. <https://doi.org/10.1016/j.jasrep.2020.102455>
- D'Alberty, L. M. (2018). Encyclopedic palace. *Studies in Digital Heritage*, 2(1), 80–94. <https://doi.org/10.14434/sdh.v2i1.24611>
- Damala, A., Ruthven, I., & Hornecker, E. (2019). The MUSETECH model: A comprehensive evaluation framework for museum technology. *Journal on Computing and Cultural Heritage*, 12(1), 1–22. <https://doi.org/10.1145/3297717>
- Deligiorgi, M., Maslioukova, M. I., Averkiou, M., Andreou, A. C., Selvaraju, P., Kalogerakis, E., Patow, G., Chrysanthou, Y., & Artopoulos, G. (2021). A 3D digitisation workflow for architecture-specific annotation of built heritage. *Journal of Archaeological Science: Reports*, 37, 102787. <https://doi.org/10.1016/j.jasrep.2020.102787>
- Deng, Y., Tang, F., Dong, W., Wu, F., Deussen, O., & Xu, C. (2019). Selective clustering for representative paintings selection. *Multimedia Tools and Applications*, 78(14), 19305–19323. <https://doi.org/10.1007/s11042-019-7271-7>
- Di Salvo, S. (2014). Innovation in lighting for enhancing the appreciation and preservation of archaeological heritage. *Journal of Cultural Heritage*, 15(2), 209–212. <https://doi.org/10.1016/j.culher.2013.03.001>
- Díaz, L., Reunanen, M., Acuña, B., & Timonen, A. (2011). ImaNote: A web-based multi-user image map viewing and annotation tool. *Journal on Computing and Cultural Heritage*, 3(4), 1–11. <https://doi.org/10.1145/1957825.1957826>
- Dimoulas, C. A., Kalliris, G. M., Chatzara, E. G., Tsiapas, N. K., & Papanikolaou, G. V. (2014). Audiovisual production, restoration-archiving and content management methods to preserve local tradition and folkloric heritage. *Journal of Cultural Heritage*, 15(3), 234–241. <https://doi.org/10.1016/j.culher.2013.05.003>
- Drakakis, A. (2020). From the material to the digital: Reflections on collecting and exhibiting grief at the 9/11 memorial museum. *Mass Violence and Memory in the Digital Age: Memorialization Unmoored* (pp. 123–140). Springer International Publishing. https://doi.org/10.1007/978-3-030-39395-3_6
- Drygalska, E. (2024). Technologically mediated experiences of visitors to the Frederic Chopin Museum postphenomenological perspective on touchscreens affordances. *Journal on Computing and Cultural Heritage*, 17(1), 1–22. <https://doi.org/10.1145/3631127>
- Echavarria, K. R., Samaroudi, M., Dibble, L., Silverton, E., & Dixon, S. (2022). Creative experiences for engaging communities with cultural heritage through place-based narratives. *Journal on Computing and Cultural Heritage*, 15(2), 1–19. <https://doi.org/10.1145/3479007>
- El-Hakim, S. F., Beraldin, J.-A., Picard, M., & Godin, G. (2004). Detailed 3D reconstruction of large-scale heritage sites with integrated techniques. *IEEE Computer Graphics and Applications*, 24(3), 21–29. <https://doi.org/10.1109/MCG.2004.1318815>
- Evans, T., & Hautekeete, L. (2011). Challenges of digital preservation for cultural heritage institutions. *Journal of Librarianship and Information Science*, 43(3), 157–165. <https://doi.org/10.1177/0961000611410585>
- Fan, Q. (2024). Research on intangible cultural heritage resource description and knowledge fusion based on linked data. *The Electronic Library*, 42(4), 521–535. <https://doi.org/10.1108/EL-01-2023-0018>
- Feng, J., Qian, Z., Chen, G., & Wang, W. (2022). A study on the importance of tactile stimulation on immersive experience for digital communication. In *The International Conference on Image, Vision and Intelligent Systems (ICIVIS 2021)* (pp. 393–401). Springer. https://doi.org/10.1007/978-981-16-6963-7_36

- Ferdani, D., Fanini, B., Piccioli, M. C., Carboni, F., & Vigliarolo, P. (2020). 3D reconstruction and validation of historical background for immersive VR applications and games: The case study of the forum of Augustus in Rome. *Journal of Cultural Heritage*, 43, 129–143. <https://doi.org/10.1016/j.culher.2019.12.004>
- Fontanella, F., Molinaro, M., Gallozzi, A., Cigola, M., Senatore, L. J., Florio, R., Clini, P., & D'Amico, F. C. (2021). HeGO, a social game as a tool for cultural heritage valorization: The case study of the Atina historical center. *Journal on Computing and Cultural Heritage*, 14(2), 1–16. <https://doi.org/10.1145/3431926>
- Franks, M. A. (2017). The desert of the unreal: Inequality in virtual and augmented reality. *University of California, Davis Law Review*, 51, 499–538. <https://doi.org/10.1215/9781478059226-003>
- Froschauer, J., Merkl, D., Arends, M., & Goldfarb, D. (2013). Art history concepts at play with ThIATRO. *Journal on Computing and Cultural Heritage*, 6(2), 1–15. <https://doi.org/10.1145/2460376.2460378>
- Gao, Z., Li, X., Liu, C., Wang, X., Wang, A., Yang, L., Wang, Y., Hui, P., & Braud, T. (2024). VR prem+: An immersive pre-learning branching visualization system for museum tours. In *Proceedings of the Eleventh International Symposium of Chinese CHI. CHCHI '23*, New York, NY (pp. 374–385). Association for Computing Machinery. <https://doi.org/10.1145/3629606.3629643>
- García-Molina, D. F., López-Lago, S., Hidalgo-Fernandez, R. E., & Triviño-Tarradas, P. (2021). Digitalization and 3D documentation techniques applied to two pieces of Visigothic sculptural heritage in Merida through structured light scanning. *Journal on Computing and Cultural Heritage*, 14(4), 1–19. <https://doi.org/10.1145/3427381>
- Gatelier, E., Ross, D., Phillips, L., & Suquet, J.-B. (2022). A business model innovation methodology for implementing digital interpretation experiences in European cultural heritage attractions. *Journal of Heritage Tourism*, 17(4), 391–408. <https://doi.org/10.1080/1743873X.2022.2065920>
- Georgopoulos, A. (2014). 3D virtual reconstruction of archaeological monuments. *Mediterranean Archaeology and Archaeometry*, 14(4), 155–164.
- Ghani, I., Rafi, A., & Woods, P. (2020). The effect of immersion towards place presence in virtual heritage environments. *Personal and Ubiquitous Computing*, 24(6), 861–872. <https://doi.org/10.1007/s00779-019-01352-8>
- Giaccardi, E., & Palen, L. (2008). The social production of heritage through cross-media interaction: Making place for place-making. *International Journal of Heritage Studies*, 14(3), 281–297. <https://doi.org/10.1080/13527250801953827>
- Gil-Melitón, M., & Lerma, J. L. (2019). Historical military heritage: 3D digitisation of the Nasri sword attributed to Ali Atar. *Virtual Archaeology Review*, 10(20), 52–69. <https://doi.org/10.4995/var.2019.10028>
- Gomes, L., Regina Pereira Bellon, O., & Silva, L. (2014). 3d reconstruction methods for digital preservation of cultural heritage: A survey. *Pattern Recognition Letters*, 50, 3–14. <https://doi.org/10.1016/j.patrec.2014.03.023>
- González Zarandona, J. A., Albarrán-Torres, C., & Isakhan, B. (2018). Digitally mediated iconoclasm: The Islamic state and the war on cultural heritage. *International Journal of Heritage Studies*, 24(6), 649–671. <https://doi.org/10.1080/13527258.2017.1413675>
- Grainger Clemson, H. (2014). Trailfinders—curating an interactive city promenade experience with mobile phones. *Digital Creativity*, 25(4), 330–342. <https://doi.org/10.1080/14626268.2014.904362>
- Green, D., Hargood, C., & Charles, F. (2021). Use of tools: UX principles for interactive narrative authoring tools. *Journal on Computing and Cultural Heritage*, 14(3), 1–25. <https://doi.org/10.1145/3458769>
- Gutierrez, D., Frischer, B., Cerezo, E., Gomez, A., & Seron, F. (2007). AI and virtual crowds: Populating the colosseum. *Journal of Cultural Heritage*, 8(2), 176–185. <https://doi.org/10.1016/j.culher.2007.01.007>
- Hamad, A., & Jia, B. (2022). How virtual reality technology has changed our lives: An overview of the current and potential applications and limitations. *International Journal of Environmental Research and Public Health*, 19(18), 11278. <https://doi.org/10.3390/ijerph191811278>
- Hamady, R., Ma, M., & Strathearn, C. (2020). Ambient information visualisation and visitors' technology acceptance of mixed reality in museums. *Journal on Computing and Cultural Heritage*, 13(2), 1–22. <https://doi.org/10.1145/3359590>
- Han, P.-H., Chen, Y.-S., Liu, I.-S., Jang, Y.-P., Tsai, L., Chang, A., & Hung, Y.-P. (2020). A compelling virtual tour of the Dunhuang cave with an immersive head-mounted display. *IEEE Computer Graphics and Applications*, 40(1), 40–55. <https://doi.org/10.1109/MCG.2019.2936753>
- Han, X.-F., Laga, H., & Bennamoun, M. (2021). Image-based 3D object reconstruction: State-of-the-art and trends in the deep learning era. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 43(5), 1578–1604. <https://doi.org/10.1109/TPAMI.2019.2954885>
- Handa, M., Aul, E. G., & Bajaj, S. (2012). Immersive technology—uses, challenges and opportunities. *International Journal of Computing & Business Research*, 6(2), 1–11.
- Hassani, F. (2015). Documentation of cultural heritage; techniques, potentials, and constraints. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XL(5/W7), 207–214. <https://doi.org/10.5194/isprsarchives-XL-5-W7-207-2015>
- Havemann, S., Settgast, V., Fellner, D., Willems, G., Van Gool, L., Muller, G., Schneider, M., & Klein, R. (2008). The presentation of cultural heritage models in epoch. In *Open Digital Cultural Heritage Systems, EPOCH Final Event Rome*. EPOCH (European Network of Excellence in Open Cultural Heritage)/EPOCH Project.
- He, W., Li, X., Xu, S., Chen, Y., Sio, C.-I., Kan, G. L., & Lee, L.-H. (2024). Metadragonboat: Exploring paddling techniques of virtual dragon boating in a metaverse campus. In *Proceedings of the 32nd ACM International Conference on Multimedia*. MM '24, New York, NY (pp. 6335–6344). Association for Computing Machinery. <https://doi.org/10.1145/3664647.3681078>
- Hess, M., Robson, S., Serpico, M., Amati, G., Pridden, I., & Nelson, T. (2016). Developing 3D imaging programmes—workflow and quality control. *Journal on Computing and Cultural Heritage*, 9(1), 1–11. <https://doi.org/10.1145/2786760>
- Hong, M., Jung, J. J., Piccialli, F., & Chianese, A. (2017). Social recommendation service for cultural heritage. *Personal and Ubiquitous Computing*, 21(2), 191–201. <https://doi.org/10.1007/s00779-016-0985-x>
- Hou, Y., Kenderdine, S., Picca, D., Egloff, M., & Adamou, A. (2022). Digitizing intangible cultural heritage embodied: State of the art. *Journal on Computing and Cultural Heritage*, 15(3), 1–20. <https://doi.org/10.1145/3494837>
- Hu, J. (2024). Individually integrated virtual/augmented reality environment for interactive perception of cultural heritage. *Journal on Computing and Cultural Heritage*, 17(1), 1–14. <https://doi.org/10.1145/3631145>
- Hulusic, V., Gusia, L., Luci, N., & Smith, M. (2023). Tangible user interfaces for enhancing user experience of virtual reality cultural heritage applications for utilization in educational environment. *Journal on Computing and Cultural Heritage*, 16(2), 1–24. <https://doi.org/10.1145/3593429>
- Idris, M. Z., Mustafa, N. B., & Yusoff, S. O. S. (2016). Preservation of intangible cultural heritage using advance digital technology: Issues and challenges. *Harmonia: Journal of Arts Research and Education*, 16(1), 1. <https://doi.org/10.15294/harmonia.v16i1.6353>
- 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/10.3390/su16156446>
- Jacobs, K., & Loscos, C. (2006). Classification of illumination methods for mixed reality. *Computer Graphics Forum*, 25(1), 29–51. <https://doi.org/10.1111/j.1467-8659.2006.00816.x>
- Jaillot, V., Istasse, M., Servigne, S., Gesquière, G., Rautenberg, M., & Lefort, I. (2020). Describing, comparing and analysing digital urban heritage tools: A methodology designed with a multidisciplinary approach. *Digital Applications in Archaeology and Cultural Heritage*, 17, e00135. <https://doi.org/10.1016/j.daach.2020.e00135>
- Jang, S.-Y., & Kim, S.-A. (2022). Content curation for spatial experience of architectural heritage. *Journal on Computing and Cultural Heritage*, 15(4), 1–41. <https://doi.org/10.1145/3513136>
- Jiang, Y., Guo, R., Ma, F., & Shi, J. (2019). Cloth simulation for Chinese traditional costumes. *Multimedia Tools and Applications*, 78(4), 5025–5050. <https://doi.org/10.1007/s11042-018-5983-8>

- Johnson, N. F. (2004, November 28–December 2). *Technological disadvantage of the digital age* [Paper presentation]. Proceedings of The Annual Conference of the Australian Association for Research in Education, University of Melbourne, Australia.
- Jones, C. E. K., Theodosios, S., & Lykourantzou, I. (2019). The enthusiast, the interested, the sceptic, and the cynic: Understanding user experience and perceived value in location-based cultural heritage games through qualitative and sentiment analysis. *Journal on Computing and Cultural Heritage*, 12(1), 1–26. <https://doi.org/10.1145/3297716>
- Kamariotou, V., Kamariotou, M., & Kitsios, F. (2021). Strategic planning for virtual exhibitions and visitors' experience: A multidisciplinary approach for museums in the digital age. *Digital Applications in Archaeology and Cultural Heritage*, 21, e00183. <https://doi.org/10.1016/j.daach.2021.e00183>
- Katifori, A., Perry, S., Vayanou, M., Antoniou, A., Ioannidis, I.-P., McKinney, S., Chrysanthi, A., & Ioannidis, Y. (2020). "Let them talk!": Exploring guided group interaction in digital storytelling experiences. *Journal on Computing and Cultural Heritage*, 13(3), 1–30. <https://doi.org/10.1145/3382773>
- Keep, T. (2022). The Mernda VR project: The creation of a VR reconstruction of an Australian heritage site. *Journal of Computer Applications in Archaeology*, 5(1), 238–254. <https://doi.org/10.5334/jcaa.91>
- Kersten, T. P., Tschirschwitz, F., Deggim, S., & Lindstaedt, M. (2018). Virtual reality for cultural heritage monuments—from 3D data recording to immersive visualisation. In *Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection: 7th International Conference, EuroMed 2018, Nicosia, Cyprus, October 29–November 3, Proceedings, Part II 7* (pp. 74–83). Springer. https://doi.org/10.1007/978-3-030-01765-1_9
- Kersten, T. P., Tschirschwitz, F., Lindstaedt, M., & Deggim, S. (2018). The historic wooden model of Solomon's temple: 3D recording, modelling and immersive virtual reality visualisation. *Journal of Cultural Heritage Management and Sustainable Development*, 8(4), 448–464. <https://doi.org/10.1108/JCHMSD-09-2017-0067>
- Kim, H., Matuszka, T., Kim, J.-I., Kim, J., & Woo, W. (2017). Ontology-based mobile augmented reality in cultural heritage sites: Information modeling and user study. *Multimedia Tools and Applications*, 76(24), 26001–26029. <https://doi.org/10.1007/s11042-017-4868-6>
- Klinowski, M., & Szafarowicz, K. (2023). Digitisation and sharing of collections: Museum practices and copyright during the covid-19 pandemic. *International Journal for the Semiotics of Law=Revue internationale de semiotique juridique*, 36(5), 1–29. <https://doi.org/10.1007/s11196-023-09986-x>
- Koller, D., Frischer, B., & Humphreys, G. (2009). Research challenges for digital archives of 3D cultural heritage models. *Journal on Computing and Cultural Heritage*, 2(3), 1–17. <https://doi.org/10.1145/1658346.1658347>
- Konstantakis, M., & Caridakis, G. (2020). Adding culture to UX: UX research methodologies and applications in cultural heritage. *Journal on Computing and Cultural Heritage*, 13(1), 1–17. <https://doi.org/10.1145/3354002>
- Król, K., & Hernik, J. (2006). *Digital heritage. Reflection of Our Activities*. Routledge. <https://doi.org/10.4324/9780080455303>
- Krumpen, S., Klein, R., & Weinmann, M. (2021). Towards tangible cultural heritage experiences – Enriching VR-based object inspection with haptic feedback. arXiv. *Journal on Computing and Cultural Heritage*, 15(1), 1–17. <https://doi.org/10.1145/3470470>
- Kukreja, V., Singh, A., Kaur, D., & Kaur Bajwa, J. (2024). *Digital cultural heritage: Challenges, solutions, and future directions* (1st ed.). CRC Press. <https://doi.org/10.1201/9781032630564>
- Kuna, J., Jeremicz, J., Kociuba, D., Niedźwiadek, R., Janus, K., & Chachaj, J. (2022). Interactive HGIS platform union of Lublin (1569): A geomatic solution for discovering the jagiellonian heritage of the city. *Journal of Cultural Heritage*, 53, 47–71. <https://doi.org/10.1016/j.culher.2021.11.001>
- Kuroczyński, P. (2017). Virtual research environment for digital 3D reconstructions: Standards, thresholds, and prospects. *Studies in Digital Heritage*, 1(2), 456–476. <https://doi.org/10.14434/sdh.v1i2.23330>
- Laskowska, M., & Marcyński, K. (2016). Purity in the media on the basis of the films 50 shades of grey and caroline. *Studia Elckie*, 18(3), 255–268. <https://www.studielckie.pl/pl/18-2016-nr-3>
- Lassandro, P., Fioriello, C. S., Lepore, M., & Zonno, M. (2021). Analysing, modelling and promoting tangible and intangible values of building heritage with historic flame lighting system. *Journal of Cultural Heritage*, 47, 166–179. <https://doi.org/10.1016/j.culher.2020.09.013>
- Lázaro, G. R., Martínez-Fernández, A., Rangel-Rivero, A., & Benito-Calvo, A. (2021). Shedding light on pre-Columbian crania collections through state-of-the-art 3D scanning techniques. *Virtual Archaeology Review*, 12(24), 1–10. <https://doi.org/10.4995/var.2021.13742>
- Lee, Y.-C. N., Shan, L.-T., & Chen, C.-H. (2013, July 21–26). System development of immersive technology theatre in museum. In *Virtual, Augmented and Mixed Reality. Systems and Applications: 5th International Conference, VAMR 2013, Held as Part of HCI International 2013, Las Vegas, NV, Proceedings, Part II 5* (pp. 400–408). Springer. https://doi.org/10.1007/978-3-642-39420-1_42
- Leonov, A. V., Anikushkin, M. N., Ivanov, A. V., Ovcharov, S. V., Bobkov, A. E., & Baturin, Y. M. (2015). Laser scanning and 3d modeling of the Shukhov hyperboloid tower in Moscow. *Journal of Cultural Heritage*, 16(4), 551–559. <https://doi.org/10.1016/j.culher.2014.09.014>
- Leow, F.-T., & Ch'ng, E. (2021). Analysing narrative engagement with immersive environments: Designing audience-centric experiences for cultural heritage learning. *Museum Management and Curatorship*, 36(4), 342–361. <https://doi.org/10.1080/09647775.2021.1914136>
- Li, H., & Hua, J. (2024). Study on the diseases classification and definition of grottoes and rock carvings. *International Association for Engineering Geology and the Environment*, 331–346. https://doi.org/10.1007/978-981-99-9203-4_23
- Li, H., & Ito, H. (2021). Comparative analysis of information tendency and application features for projection mapping technologies at cultural heritage sites. *Heritage Science*, 9(1), 126. <https://doi.org/10.1186/s40494-021-00579-0>
- Li, H., & Ito, H. (2023). Visitor's experience evaluation of applied projection mapping technology at cultural heritage and tourism sites: The case of China Tangcheng. *Heritage Science*, 11(1), 52. <https://doi.org/10.1186/s40494-023-00898-4>
- Li, J., & Kim, K. S. (2023). Kano-QFD-based analysis of the influence of user experience on the design of handicraft intangible cultural heritage apps. *Heritage Science*, 11(1), 59. <https://doi.org/10.1186/s40494-023-00903-w>
- Li, J., Xu, T., Gu, X., Lin, J., Li, M., Tao, P., Dong, X., Yao, P., & Shao, M. (2023). Scene clusters, causes, spatial patterns and strategies in the cultural landscape heritage of tang poetry road in eastern Zhejiang based on text mining. *Heritage Science*, 11(1), 212. <https://doi.org/10.1186/s40494-023-01051-x>
- Li, R. Y.-C., & Liew, A. W.-C. (2015). An interactive user interface prototype design for enhancing on-site museum and art gallery experience through digital technology. *Museum Management and Curatorship*, 30(3), 208–229. <https://doi.org/10.1080/09647775.2015.1042509>
- Liang, H., Li, W., & Zhang, Q. (2019). Semantic-based 3D information modelling and documentation of rockeries in Chinese classical gardens: A case study on the rockery at Huanxiu Shanzhuang, Suzhou, China. *Journal of Cultural Heritage*, 37, 247–258. <https://doi.org/10.1016/j.culher.2018.11.015>
- Liew, C. L. (2014). Towards dynamic and evolving digital libraries. *Electronic Library*, 32(1), 2–16. <https://doi.org/10.1108/EL-07-2012-0089>
- Liritzis, I., Al-Otaibi, F. M., Volonakis, P., & Drivaliari, A. (2015). Digital technologies and trends in cultural heritage. *Mediterranean Archaeology and Archaeometry*, 15(3), 313–332. <https://doi.org/10.5281/zenodo.33832>
- Liu, Q. X., Duan, Y. H., & Deng, J. Y. (2012). Geological protection project of the longmen grottoes in luoyang. *Advanced Materials Research*, 594–597, 155–160. <https://doi.org/10.4028/www.scientific.net/AMR.594-597.155>

- Loaiza Carvajal, D. A., Morita, M. M., & Bilmes, G. M. (2020). Virtual museums. captured reality and 3d modeling. *Journal of Cultural Heritage*, 45, 234–239. <https://doi.org/10.1016/j.culher.2020.04.013>
- Lu, L., & Li, M. (2023). Development of a virtual interactive system for Dahua Lou loom based on knowledge ontology-driven technology. *Heritage Science*, 11(1), 178. <https://doi.org/10.1186/s40494-023-01027-x>
- Lutz, B., & Weintke, M. (1999). Virtual dunhuang art cave: A cave within a CAVE. *Computer Graphics Forum*, 18(3), 257–264. <https://doi.org/10.1111/1467-8659.00346>
- Lužnik-Jancsary, N., Horejs, B., Klein, M., & Schwall, C. (2020). Integration and workflow framework for virtual visualisation of cultural heritage. Revisiting the tell of Cukurici Hoyuk, turkey. *Virtual Archaeology Review*, 11(23), 63–74. <https://doi.org/10.4995/var.2020.13086>
- Ma, D., Xu, J., & Pu, P. (2023). Spreading and application of digital media art to traditional handicrafts-taking tie dyeing of bai nationality as an example. *Computer-Aided Design and Applications*, 20, 147–158. <https://doi.org/10.14733/cadaps.2023.S8.147-158>
- Machidon, O.-M., Tăvcar, A., Gams, M., & Duguleană, M. (2020). CulturalERICA: A conversational agent improving the exploration of European cultural heritage. *Journal of Cultural Heritage*, 41, 152–165. <https://doi.org/10.1016/j.culher.2019.07.010>
- Mah, O. B. P., Yan, Y., Tan, J. S. Y., Tan, Y.-X., Tay, G. Q. Y., Chiam, D. J., Wang, Y.-C., Dean, K., & Feng, C.-C. (2019). Generating a virtual tour for the preservation of the (in)tangible cultural heritage of Tampines Chinese temple in Singapore. *Journal of Cultural Heritage*, 39, 202–211. <https://doi.org/10.1016/j.culher.2019.04.004>
- Malik, U. S., Tissen, L. N. M., & Vermeeren, A. P. O. S. (2021). 3D reproductions of cultural heritage artifacts: Evaluation of significance and experience. *Studies in Digital Heritage*, 5(1), 1–29. <https://doi.org/10.14434/sdh.v5i1.32323>
- Manzuch, Z. (2017). Ethical issues in digitization of cultural heritage. *Journal of Contemporary Archival Studies*, 4(2), 4. <https://doi.org/10.2788/8472>
- Marcos, A. F. (2007). Digital art: When artistic and cultural muse merges with computer technology. *IEEE Computer Graphics and Applications*, 27(5), 98–103. <https://doi.org/10.1109/MCG.2007.123>
- Marsili, G., & Orlandi, L. M. (2020). Digital humanities and cultural heritage preservation: The case of the BYZART (Byzantine art and archaeology on Europeana) project. *Studies in Digital Heritage*, 3(2), 144–155. <https://doi.org/10.14434/sdh.v3i2.27721>
- Mas, M. T., Bendicho, V.-M., Tercero, J. L., Valdelomar, J. T., & Maschner, H. (2021). Digitization and virtual reality projects in archaeological heritage. The case of the archaeological site of Motilla del Azuer in Daimiel (Ciudad real). *Virtual Archaeology Review*, 13(26), 135–146. <https://doi.org/10.4995/VAR.2022.15004>
- Méndez, A., Martín, L., Arines, J., Carballeira, R., & Sanmartín, P. (2022). Attraction of insects to ornamental lighting used on cultural heritage buildings: A case study in an urban area. *Insects*, 13(12), 1153. <https://doi.org/10.3390/insects13121153>
- Menna, F., & Nocerino, E. (2014). Hybrid survey method for 3D digital recording and documentation of maritime heritage. *Applied Geomatics*, 6(2), 81–93. <https://doi.org/10.1007/s12518-011-0074-9>
- Millard, D. E., Packer, H., Howard, Y., & Hargood, C. (2020). The balance of attention: The challenges of creating locative cultural storytelling experiences. *Journal on Computing and Cultural Heritage*, 13(4), 1–24. <https://doi.org/10.1145/3404195>
- Monaco, D., Pellegrino, M. A., Scarano, V., & Viciomini, L. (2022). Linked open data in authoring virtual exhibitions. *Journal of Cultural Heritage*, 53, 127–142. <https://doi.org/10.1016/j.culher.2021.11.002>
- Montusiewicz, J., & Milosz, M. (2021). Architectural jewels of lublin: A modern computerized board game in cultural heritage education. *Journal on Computing and Cultural Heritage*, 14(3), 1–21. <https://doi.org/10.1145/3446978>
- Muir, H. (2009). eResearch: The institutional repository experience at Queen Margaret University, Edinburgh. *SCONUL Focus*, 46, 51–54.
- Mulumba, O., Irenea, K. O., Kumah, M. A., & Bulugu, P. P. (2017). Institutional repositories containing digitized heritage material (special collections) are making 'lost or hidden' cultures accessible: Advantages and disadvantages of this trend. *IOSR Journal of Humanities and Social Science (IOSR-JHSS)*, 22(9), 30–38. <https://doi.org/10.9790/0837-2209063038>
- Nancarrow, J.-H. (2020). Countering the “digital uncanny”: Post-processing for 3-D digital heritage. *Studies in Digital Heritage*, 3(2), 170–185. <https://doi.org/10.14434/sdh.v3i2.27748>
- Neamțu, C., Comes, R., Popovici, D.-M., Băutu, E., Liliana, M.-S., Syrotnik, A., & Popovici, M.-I. (2024). Evaluating user experience in the context of cultural heritage dissemination using extended reality: A case study of the Dacian Bronze Matrix with hollow design. *Journal on Computing and Cultural Heritage*, 17(2), 1–21. <https://doi.org/10.1145/3639933>
- Neudecker, C., & Tzadok, A. (2010). User collaboration for improving access to historical texts. *LIBER Quarterly: The Journal of the Association of European Research Libraries*, 20(1), 119–128. <https://doi.org/10.18352/lq.7981>
- Newell, J. (2012). Old objects, new media: Historical collections, digitization and affect. *Journal of Material Culture*, 17(3), 287–306. <https://doi.org/10.1177/1359183512453534>
- Noardo, F. (2018). Architectural heritage semantic 3D documentation in multi-scale standard maps. *Journal of Cultural Heritage*, 32, 156–165. <https://doi.org/10.1016/j.culher.2018.02.009>
- Nofal, E., Reffat, R. M., & Moere, A. V. (2017). *Phygital heritage: An approach for heritage communication* [Paper presentation]. Verlag der Technischen Universität Graz. <https://doi.org/10.3217/978-3-85125-530-0-36>
- Not, E., Cavada, D., Maule, S., Pisetti, A., & Venturini, A. (2019). Digital augmentation of historical objects through tangible interaction. *Journal on Computing and Cultural Heritage*, 12(3), 1–19. <https://doi.org/10.1145/3297764>
- O'dwyer, N., Zerman, E., Young, G. W., Smolic, A., Dunne, S., & Shenton, H. (2021). Volumetric video in augmented reality applications for museological narratives: A user study for the long room in the library of trinity college Dublin. *Journal on Computing and Cultural Heritage*, 14(2), 1–20. <https://doi.org/10.1145/3425400>
- Ocón, D. (2021). Digitalising endangered cultural heritage in southeast Asian cities: Preserving or replacing? *International Journal of Heritage Studies*, 27(10), 975–990. <https://doi.org/10.1080/13527258.2021.1883711>
- Ocón, D. (2023). Low-cost digital tools to preserve cultural heritage 'blind spots': The case of kubor kassim in singapore. *International Journal of Heritage Studies*, 29(9), 961–987. <https://doi.org/10.1080/13527258.2023.2231903>
- Oomen, J., & Aroyo, L. (2011). Crowdsourcing in the cultural heritage domain: Opportunities and challenges. In *Proceedings of the 5th International Conference on Communities and Technologies* (pp. 138–149). ACM. <https://doi.org/10.1145/2103354.2103373>
- Ott, M., & Pozzi, F. (2011). Towards a new era for cultural heritage education: Discussing the role of ICT. *Computers in Human Behavior*, 27(4), 1365–1371. <https://doi.org/10.1145/2103354.2103373>
- Permatasari, P. A., Qohar, A. A., & Rachman, A. F. (2020). From web 1.0 to web 4.0: The digital heritage platforms for UNESCO's heritage properties in Indonesia. *Virtual Archaeology Review*, 11(23), 75–93. <https://doi.org/10.4995/var.2020.13121>
- Peters, D., Brenzinger, M., Meyer, R., Noble, A., & Zimmer, N. (2015). The digital library in the re-inscription of African cultural heritage. *IFLA Journal*, 41(3), 204–210. <https://doi.org/10.1177/0340035215603990>
- Petrelli, D., & Roberts, A. J. (2023). Exploring digital means to engage visitors with roman culture: Virtual reality vs. tangible interaction. *Journal on Computing and Cultural Heritage*, 16(4), 1–18. <https://doi.org/10.1145/3625367>
- Petrovič, D., Grigillo, D., Kosmatin Fras, M., Urbančič, T., & Kozmus Trajkovski, K. (2021). Geodetic methods for documenting and modeling cultural heritage objects. *International Journal of Architectural Heritage*, 15(6), 885–896. <https://doi.org/10.1080/15583058.2019.1683779>
- Piccialli, F., & Chianese, A. (2017). Cultural heritage and new technologies: Trends and challenges. *Personal and Ubiquitous Computing*, 21(2), 187–189. <https://doi.org/10.1007/s00779-016-0984-y>

- Pietroni, E., & Adami, A. (2014). Interacting with virtual reconstructions in museums: The etruscanning project. *Journal on Computing and Cultural Heritage*, 7(2), 1–29. <https://doi.org/10.1145/2611375>
- Pistofidis, P., Arnaoutoglou, F., Ioannakis, G., Michailidou, N., Karta, M., Kiourt, C., Pavlidis, G., Mouroutsos, S. G., Tsiafaki, D., & Koutsoudis, A. (2023). Design and evaluation of smart-exhibit systems that enrich cultural heritage experiences for the visually impaired. *Journal of Cultural Heritage*, 60, 1–11. <https://doi.org/10.1108/EL-01-2023-0018>
- Portalés, C., Pérez, M., Casanova-Salas, P., & Gimeno, J. (2021). Virtual loom: A tool for the interactive 3D representation of historical fabrics. *Multimedia Tools and Applications*, 80(9), 13735–13760. <https://doi.org/10.1007/s11042-020-10294-w>
- Psomadaki, O. I., Dimoulas, C. A., Kalliris, G. M., & Paschalidis, G. (2019). Digital storytelling and audience engagement in cultural heritage management: A collaborative model based on the digital city of Thessaloniki. *Journal of Cultural Heritage*, 36, 12–22. <https://doi.org/10.1016/j.culher.2018.07.016>
- Qi, Z., Kang, C., Wang, P., & Li, W. (2023). Application of digital art technology in architectural heritage preservation and digital reconstruction in the construction industry. *Computer-Aided Design and Applications*, 21(1), 14–27. <https://doi.org/10.14733/cadaps.2024.S11.14-27>
- Quattrini, R., Pierdicca, R., Paolanti, M., Clini, P., Nespeca, R., & Frontoni, E. (2020). Digital interaction with 3D archaeological artefacts: Evaluating user's behaviours at different representation scales. *Digital Applications in Archaeology and Cultural Heritage*, 18, e00148. <https://doi.org/10.1016/j.daach.2020.e00148>
- Rahaman, H., Champion, E., & Bekele, M. (2019). From photo to 3D to mixed reality: A complete workflow for cultural heritage visualisation and experience. *Digital Applications in Archaeology and Cultural Heritage*, 13, e00102. <https://doi.org/10.1016/j.daach.2019.e00102>
- Raheb, K. E., Stergiou, M., Katifori, A., & Ioannidis, Y. (2021). Moving in the cube: A motion-based playful experience for introducing lab-notation to beginners. *Journal on Computing and Cultural Heritage*, 14(2), 1–26. <https://doi.org/10.1145/3427379>
- Rattanakongrot, S., Kalarat, K., White, M., & Chaisriya, K. (2024). Preserving southern Thai traditional manora dance through mobile role-playing game technology. *Journal on Computing and Cultural Heritage*, 17(1), 1–22. <https://doi.org/10.1145/3631122>
- Reerink, H. (2012). UNICUM: A portal to Dutch academic heritage. *LIBER Quarterly: The Journal of the Association of European Research Libraries*, 21(2), 226–237. <https://doi.org/10.18352/lq.8021>
- Renzi, G., Rinaldi, A. M., Russo, C., & Tommasino, C. (2023). A storytelling framework based on multimedia knowledge graph using linked open data and deep neural networks. *Multimedia Tools and Applications*, 82(20), 31625–31639. <https://doi.org/10.1007/s11042-023-14398-x>
- Ricart, S., Ribas, A., Pavón, D., Gabarda-Mallorquí, A., & Roset, D. (2019). Promoting historical irrigation canals as natural and cultural heritage in mass-tourism destinations. *Journal of Cultural Heritage Management and Sustainable Development*, 9(4), 520–536. <https://doi.org/10.1108/JCHMSD-12-2017-0089>
- Ridel, B., Reuter, P., Laviolle, J., Mellado, N., Couture, N., & Granier, X. (2014). The revealing flashlight: Interactive spatial augmented reality for detail exploration of cultural heritage artifacts. *Journal on Computing and Cultural Heritage*, 7(2), 1–18. <https://doi.org/10.1145/2611376>
- Rojas-Sola, J. I., & Fuente, E. (2018). Digital 3D reconstruction of Betancourt's historical heritage: The dredging machine in the port of Kronstadt. *Virtual Archaeology Review*, 9(18), 44–56. <https://doi.org/10.4995/var.2018.7946>
- Ruffino, P. A., Permedi, D., Gandino, E., Haron, A., Osello, A., & Wong, C. O. (2019). Digital technologies for inclusive cultural heritage: The case study of Serralunga D'alba castle. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, IV-2/W6, 141–147. <https://doi.org/10.5194/isprs-annals-IV-2-W6-141-2019>
- Scopigno, R., Callieri, M., Dellepiane, M., Ponchio, F., & Potenzi, M. (2017). Delivering and using 3D models on the web: Are we ready? *Virtual Archaeology Review*, 8(17), 1–9. <https://doi.org/10.4995/var.2017.6405>
- Semeraro, G., Lops, P., De Gemmis, M., Musto, C., & Narducci, F. (2012). A Folksonomy-based recommender system for personalized access to digital artworks. *Journal on Computing and Cultural Heritage*, 5(3), 1–22. <https://doi.org/10.1145/2362402.2362405>
- Serain, C. (2018). The sensitive perception of cultural heritage's materiality through digital technologies. *Studies in Digital Heritage*, 2(1), 95–105. <https://doi.org/10.14434/sdh.v2i1.24606>
- Sertalp, E., Emmez, Y., Bütün, E., Doğan, E., & Büyükkarakaya, A. M. (2023). Raising public awareness of at-risk cultural heritage through new methods of digital archaeology: The case of the “faces of juliopolis” exhibition. *Mediterranean Archaeology and Archaeometry*, 23(2), 175–195. <https://doi.org/10.5281/zenodo.8179461>
- Simone, C., Cerquetti, M., & La Sala, A. (2021). Museums in the infosphere: Reshaping value creation. *Museum Management and Curatorship*, 36(4), 322–341. <https://doi.org/10.1080/09647775.2021.1914140>
- Smirnov, A. V., Kashevnik, A. M., & Ponomarev, A. (2017). Context-based infomobility system for cultural heritage recommendation: Tourist assistant—TAIS. *Personal and Ubiquitous Computing*, 21(2), 297–311. <https://doi.org/10.1007/s00779-016-0990-0>
- Smith, M., Walford, N. S., & Jimenez-Bescos, C. (2018). Assessing the user response to differences in functionality when visualising 3D models of cultural heritage sites using the technology readiness index. *Digital Applications in Archaeology and Cultural Heritage*, 10, e00076. <https://doi.org/10.1016/j.daach.2018.e00076>
- Smith, R. C., & Iversen, O. S. (2014). Participatory heritage innovation: Designing dialogic sites of engagement. *Digital Creativity*, 25(3), 255–268. <https://doi.org/10.1080/14626268.2014.904796>
- Smithies, J., Flohr, P., Bala'awi, F., Idwan, S., Palmer, C., Esposito, A., Mubaideen, S., & Rababeh, S. (2022). MaDiH (): A transnational approach to building digital cultural heritage capacity. *Journal on Computing and Cultural Heritage*, 15(4), 1–14. <https://doi.org/10.1145/3513261>
- Solima, L., & Izzo, F. (2018). QR codes in cultural heritage tourism: New communications technologies and future prospects in Naples and Warsaw. *Journal of Heritage Tourism*, 13(2), 115–127. <https://doi.org/10.1080/1743873X.2017.1337776>
- Spagnolo, G. S., Cozzella, L., & Leccese, F. (2021). Fringe-projection profilometry for recovering 2.5D shape of ancient coins. *ACTA IMEKO*, 10(1), 142–149. https://doi.org/10.21014/acta_imeko.v10i1.872
- Staropoli, L., Acevedo, V. J., Ávido, D. N., & Vitores, M. (2023). Reflections of the practice of digital archaeology: Virtual cultural heritage construction and communication. *Virtual Archaeology Review*, 14(29), 118–135. <https://doi.org/10.4995/var.2023.19292>
- Stichelbaut, B., Plets, G., & Reeves, K. (2021). Towards an inclusive curation of WWI heritage: Integrating historical aerial photographs, digital museum applications and landscape markers in “flanders fields” (Belgium). *Journal of Cultural Heritage Management and Sustainable Development*, 11(4), 344–360. <https://doi.org/10.1108/JCHMSD-04-2020-0056>
- Storeide, M. S. B., George, S., Sole, A., & Hardeberg, J. Y. (2023). Standardization of digitized heritage: A review of implementations of 3D in cultural heritage. *Heritage Science*, 11(1), 249. <https://doi.org/10.1186/s40494-023-01079-z>
- Styliadis, A. D., Akbaylar, I. I., Papadopoulou, D. A., Hasanagas, N. D., Roussa, S. A., & Sexidis, L. A. (2009). Metadata-based heritage sites modeling with e-learning functionality. *Journal of Cultural Heritage*, 10(2), 296–312. <https://doi.org/10.1016/j.culher.2008.08.014>
- Suh, A., & Prophet, J. (2018). The state of immersive technology research: A literature analysis. *Computers in Human Behavior*, 86, 77–90. https://doi.org/10.1007/978-3-642-39420-1_42
- Suominen, J., & Sivula, A. (2013). Gaming legacy? Four approaches to the relation between cultural heritage and digital technology. *Journal on Computing and Cultural Heritage*, 6(3), 1–18. <https://doi.org/10.1145/2499931.2499933>
- Sutcliffe, K., & Kim, S. (2014). Understanding children's engagement with interpretation at a cultural heritage museum. *Journal of Heritage Tourism*, 9(4), 332–348. <https://doi.org/10.1080/1743873X.2014.924952>
- Szabo, V., Lacedelli, S. Z., & Pompanin, G. (2017). From landscape to cities: A participatory approach to the creation of digital cultural

- heritage. *International Information & Library Review*, 49(2), 115–123. <https://doi.org/10.1080/10572317.2017.1314141>
- Tai, N.-C., & Sung, L.-W. (2019). Digital archiving of perceptual experiences of an architectural space with computer-aided methods. *Computer-Aided Design and Applications*, 17(3), 585–597. <https://doi.org/10.14733/cadaps.2020.585-597>
- Themistocleous, K. (2017). Model reconstruction for 3D visualization of cultural heritage sites using open data from social media: The case study of Soli, Cyprus. *Journal of Archaeological Science: Reports*, 14, 774–781. <https://doi.org/10.1016/j.jasrep.2016.08.045>
- Tong, Y., Cai, Y., Nevin, A., & Ma, Q. (2023). Digital technology virtual restoration of the colours and textures of polychrome Bodhidharma statue from the Lingyan temple, Shandong, China. *Heritage Science*, 11(1), 12. <https://doi.org/10.1186/s40494-023-00858-y>
- Trunfio, M., Campana, S., & Magnelli, A. (2023). Experimenting hybrid reality in cultural heritage reconstruction. The peasant civilisation park and the ‘vicinato a pozzo’ museum of Matera (Italy). *Museum Management and Curatorship*, 38(4), 428–450. <https://doi.org/10.1080/09647775.2022.2052159>
- Tsiviltidou, Z., & Vavoula, G. (2023). Digital stories with the online collection of the V&A for inquiry-based learning. *Journal on Computing and Cultural Heritage*, 16(1), 1–23. <https://doi.org/10.1145/3570330>
- Verovnik, R., Fišer, Ž., & Zakšek, V. (2015). How to reduce the impact of artificial lighting on moths: A case study on cultural heritage sites in Slovenia. *Journal for Nature Conservation*, 28, 105–111. <https://doi.org/10.1016/j.jnc.2015.09.002>
- Vilbrandt, T., Vilbrandt, C., Pasko, G. I., Stamm, C., & Pasko, A. (2011). Digitally interpreting traditional folk crafts. *IEEE Computer Graphics and Applications*, 31(4), 12–18. <https://doi.org/10.1109/MCG.2011.57>
- Villa, V., Pignatale, T., & Tramentozzi, I. (2017). The lapidary of palazzo anciano. Digital technologies and 3D printing to improve knowledge of the stele collection. *Studies in Digital Heritage*, 1(2), 769–784. <https://doi.org/10.14434/sdh.v1i2.23252>
- Viola, L. (2023). Networks of migrants’ narratives: A post-authentic approach to heritage visualisation. *Journal on Computing and Cultural Heritage*, 16(1), 1–21. <https://doi.org/10.1145/3575863>
- Vosinakis, S., & Tsakonas, Y. (2016). Visitor experience in Google art project and in second life-based virtual museums: A comparative study. *Mediterranean Archaeology and Archaeometry*, 16(5), 19–27. <https://doi.org/10.5281/zenodo.204963>
- Vurpillot, D., Verriez, Q., & Thivet, M. (2019). Aspectus: A flexible collaboration tool for multimodal and multiscalar 3D data exploitation. *Studies in Digital Heritage*, 2(2), 150–165. <https://doi.org/10.14434/sdh.v2i2.24446>
- Wagner, A., & De Clippele, M.-S. (2023). Safeguarding cultural heritage in the digital era – a critical challenge. *International Journal for the Semiotics of Law - Revue internationale de Sémiotique juridique*, 36(5), 1915–1923. <https://doi.org/10.1007/s11196-023-10040-z>
- Wang, H., Du, J., Li, Y., Zhang, L., Li, X. (2025). Data supporting “grand challenges in immersive technologies for cultural heritage.” <https://doi.org/10.17863/CAM.115749>
- Wijnhoven, M. A., & Moskvina, A. (2020). Digital replication and reconstruction of mail armour. *Journal of Cultural Heritage*, 45, 221–233. <https://doi.org/10.1016/j.culher.2020.04.010>
- Windhager, F., Federico, P., Schreder, G., Glinka, K., Dork, M., Miksch, S., & Mayr, E. (2019). Visualization of cultural heritage collection data: State of the art and future challenges. *IEEE Transactions on Visualization and Computer Graphics*, 25(6), 2311–2330. <https://doi.org/10.1109/TVCG.2018.2830759>
- Wu, L., Yu, R., Su, W., & Ye, S. (2022). Design and implementation of a metaverse platform for traditional culture: The chime bells of Marquis Yi of Zeng. *Heritage Science*, 10(1), 193. <https://doi.org/10.1186/s40494-022-00828-w>
- Wu, S. (2024). Digital transmission of intangible cultural heritage based on empirical modal analysis in a multicultural perspective. *Applied Mathematics and Nonlinear Sciences*, 9(1). <https://doi.org/10.2478/amns.2023.2.00629>
- Xiong, W. (2023). Títul construction of non-inherited digital platform based on PEST-SWOT model. *Applied Mathematics and Nonlinear Sciences*, 8(2), 1819–1828. <https://doi.org/10.2478/amns.2023.1.00285>
- Xu, L., Lu, L., & Liu, M. (2023). Construction and application of a knowledge graph-based question answering system for Nanjing Yunjin digital resources. *Heritage Science*, 11(1), 222. <https://doi.org/10.1186/s40494-023-01068-2>
- Xue, K., Li, Y., & Meng, X. (2019). An evaluation model to assess the communication effects of intangible cultural heritage. *Journal of Cultural Heritage*, 40, 124–132. <https://doi.org/10.1016/j.culher.2019.05.021>
- Yaagoubi, R., Al-Gilani, A., Baik, A., Alhomodi, E., & Miky, Y. (2019). SEH-SDB: A semantically enriched historical spatial database for documentation and preservation of monumental heritage based on CityGML. *Applied Geomatics*, 11(1), 53–68. <https://doi.org/10.1007/s12518-018-0238-y>
- Yan, M., Xiong, R., Shen, Y., Jin, C., & Wang, Y. (2023). Intelligent generation of Peking opera facial masks with deep learning frameworks. *Heritage Science*, 11(1), 20. <https://doi.org/10.1186/s40494-023-00865-z>
- Yastikli, N. (2007). Documentation of cultural heritage using digital photogrammetry and laser scanning. *Journal of Cultural Heritage*, 8(4), 423–427. <https://doi.org/10.1016/j.culher.2007.06.003>
- Younes, G., Asmar, D., Elhadj, I., & Al-Harithy, H. (2016). Pose tracking for augmented reality applications in outdoor archaeological sites. *Journal of Electronic Imaging*, 26(01), 1. <https://doi.org/10.1117/1.JEI.26.1.011004>
- Zaia, S. E., Rose, K. E., & Majewski, A. S. (2022). Egyptian archaeology in multiple realities: Integrating XR technologies and museum outreach. *Digital Applications in Archaeology and Cultural Heritage*, 27, e00249. <https://doi.org/10.1016/i.daach.2022.e00249>
- Zhang, C., Zhang, W., & Zheng, Y. (2021). Multimedia-based computer-aided ceramic design. *Computer-Aided Design and Applications*, 18(S4), 49–60. <https://doi.org/10.14733/cadaps.2021.S4.49-60>
- Zhang, H. (2024). Reviving tradition: Leveraging cutting-edge digital technology for the preservation and promotion of intangible cultural heritage. *Mediterranean Archaeology and Archaeometry*, 24(2).
- 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, L. (2023). Personalized healthcare museum exhibition system design based on VR and deep learning driven multimedia and multimodal sensing. *Personal and Ubiquitous Computing*, 27(3), 973–988. <https://doi.org/10.1007/s00779-022-01672-2>
- Zhao, S., Kirk, D., Bowen, S., Chatting, D., & Wright, P. (2020). Supporting the cross-cultural appreciation of traditional Chinese puppetry through a digital gesture library. *Journal on Computing and Cultural Heritage*, 12(4), 1–19. <https://doi.org/10.1145/3341882>
- Zhenrao, C., Chaoyang, F., Qian, Z., & Fulong, C. (2021). Joint development of cultural heritage protection and tourism: The case of Mount Lushan cultural landscape heritage site. *Heritage Science*, 9(1), e58. <https://doi.org/10.1186/s40494-021-00558-5>
- Zhou, N. (2020). Database design of regional music characteristic culture resources based on improved neural network in data mining. *Personal and Ubiquitous Computing*, 24(1), 103–114. <https://doi.org/10.1007/s00779-019-01335-9>
- Zhu, P., & Chung, W.-J. (2024). Designing the presentation of dunhuang Fresco art based on perception technology in the context of artificial intelligence. *Applied Mathematics and Nonlinear Sciences*, 9(1). <https://doi.org/10.2478/amns.2023.2.00135>
- Zielinska-Dabkowska, K., & Xavia, K. (2018). *Historic urban settings, led illumination and its impact on nighttime perception, visual appearance, and cultural heritage identity* [Paper presentation]. Proceedings of the 5th SGEM International Multidisciplinary Scientific Conferences on Social Sciences and Arts SGEM2018, Florence, Italy, 23–26. <https://doi.org/10.5593/sgemsocialF2018/6.3/S15.033>

About the authors

Hanbing Wang is a Research Assistant at Tsinghua University, holding an MA from Goldsmiths, University of London and a BA from Beihang University. Her research focuses on digital innovation in cultural heritage, immersive experience design, and interaction design theory.

Junyan Du is a Master's student at Tsinghua University. She obtained a Bachelor's degree in Visual Communication Design from China University of Geosciences (Wuhan).

Yue Li is an Assistant Professor in the Department of Computing at Xi'an Jiaotong-Liverpool University. Her research interest is in the field

of human-computer interaction, with particular emphasis on the design, evaluation, and application of virtual and augmented reality technologies in cultural heritage and education.

Lie Zhang is a Professor at Tsinghua University, with degrees from Zhejiang University and Tsinghua. His research covers interaction design, media space art, heritage display, and autism rehabilitation.

Xiang Li is a PhD student in the Department of Engineering at the University of Cambridge and a Student Fellow at The Leverhulme Centre for the Future of Intelligence. He received his BSc (Hons) in Information and Computing Science from Xi'an Jiaotong-Liverpool University and the University of Liverpool.