Comprehensive review of digital museums: innovations, technologies, and user experiences

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Abstract

The emergence of digital technologies has significantly altered the operational dynamics of museums, facilitating innovative methods of interaction, engagement, and education. The incorporation of virtual reality (VR), augmented reality (AR), and extended reality (XR) has fostered immersive experiences that effectively connect physical and virtual realms, thereby enriching visitors' comprehension and appreciation of cultural heritage. This article presents a thorough examination of the contemporary landscape of digital museums through a review of recent scholarly literature. It emphasizes critical themes such as the emotional resonance of immersive technologies, user experiences within virtual settings, the contribution of mobile applications to enhancing museum visits, and the theoretical frameworks that inform the design of digital museum experiences. By integrating findings from various studies, this article underscores both the potential and challenges faced by digital museums and proposes avenues for future research and practice in this swiftly advancing domain.

Keywords

Virtual reality, augmented reality, extended reality, digital museums, emotional perception, mobile museum applications, immersive technologies, user experience, interactive exhibitions, cultural heritage technologies

1. Introduction

Over time, culture has played a very important role in the preservation of history and, to this end, museums have provided the necessary facilities within which objects and artistic works can be stored, researched and viewed. Previously, it was established that the possibilities of museums were rather narrow because objects could be observed only in certain places, and the interpretation could only be done through facilities that were passive and did not allow many interactions. However, the advance in the application of digital technology in the recent past several decades has expanded the opportunities that museums have as they have become more dynamic places, which are capable of providing more complex and engaging experiences. This work aims at exploring the current state of digital museums with a special emphasis on aspects of Virtual Reality (VR), Augmented

Reality (AR) and Extended Reality (XR). Examining recent articles and journals, it becomes possible to identify how these technologies increase the audience's interest, facilitate learning, and make innovative ways of narration. Along with it, important issues which arise in connection with these technologies are mentioned, including usability, impact on emotions, and the issue of content design. By means of this systematic literature review, we would like to present a systematic description of the state-of-the-art in the field of digital museums and identify their possible future developments. In addition to immersive technologies, mobile applications and interactive design

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models have also played an increasingly important role in enhancing the museum experience. These tools make digital content more accessible across various platforms and support personalized user journeys through intuitive interfaces. As museums seek to reach broader and more diverse audiences, designing flexible and user-friendly solutions becomes a central challenge. The integration of mobile and conceptual models also invites further reflection on how museums balance technology with storytelling, educational goals, and cultural preservation.

2. The rise of immersive technologies in museums

2.1 Virtual reality (VR)

Virtual reality (VR) is one of the digital museum most recognized technologies currently in use. More specifically, in VR we can put users into fully interactive digital surroundings, which can take them to another era, show recreations of cultural landmarks or monuments no longer in existence, or give the details of fragile items up close. Research has indicated that VR can enrich educational and emotional experience of visiting museums, making it more effective than most display methods. For instance, Lee et al. [1] researched on the application of technology in museums whereby VR provides a sense of environment that has an effect on multi-sensory input. The authors discovered that exposing the visitors to VR experiences, as a form of an intervention, results in a higher level of satisfaction and cognitive immersion in the content of museums especially when the museum creates environments that otherwise are not available for a visitor to experience in real life such as recreations of archaeological sites, or re-enactment of historical moments.

The last advantage of VR, which is worth mentioning, is connected to the exploration of big or difficult-to-access spaces. In the topics about the application of VR, it will be possible to show learn content that can be too delicate to display physically or is too big for that. This is done, for instance, in the study by Marín-Morales et al. [2] where the authors contrasted the use of real and virtual museums. This they observed demonstrated that VR was capable of eliciting the emotional and cognitive feelings of a physical.

2.2 Augmented reality (AR)

Virtual reality (VR) immerses users in fully digital environments, whereas augmented reality (AR) enhances the physical world by superimposing digital information, thereby enriching the interaction between visitors and tangible objects. AR has become increasingly popular in museums as a means to add supplementary layers of information and context to exhibits, enabling visitors to engage with artifacts in innovative and significant ways. Research conducted by Siang et al. [3] examined the application of AR in mobile platforms within museums. The study underscored the technology's capacity to improve user engagement with physical displays by delivering contextual details, such as historical insights or comprehensive descriptions, directly to the visitor's smartphone. This approach not only enhances the visitor experience but also enables museums to connect with a wider audience, as AR applications can be utilized remotely.

In a separate investigation, Hammady et al. [4] explored the acceptance of mixed reality technologies in museum settings, which integrate aspects of both AR and VR. Their results indicated that visitors value the enriched information and interactivity offered by AR, which can render the museum experience more captivating and educational. Nonetheless, the study emphasized the necessity of user-friendly interfaces and intuitive design, as overly complex or unwieldy technology may diminish the overall experience.

2.3 Extended reality (XR)

Extended reality (XR) serves as a comprehensive term that includes virtual reality (VR), augmented reality (AR), and mixed reality (MR), encapsulating a wide array of digital experiences that merge the

physical and virtual realms. The application of XR technologies in museums is on the rise, facilitating the development of immersive environments that can be customized to meet the diverse needs and preferences of individual visitors. A significant advancement in this domain is the notion of "X-Reality Museums," as articulated by Margetis et al. [5]. The authors suggest a conceptual framework for the incorporation of XR technologies into museum settings, allowing visitors to transition seamlessly between physical and virtual spaces. This methodology not only enriches the conventional museum experience but also opens up novel avenues for education and engagement, enabling the creation of innovative exhibits that would be unfeasible in a purely physical context. Furthermore, the integration of XR technologies in museums prompts critical considerations regarding the design and execution of these experiences.

Zou et al. [6] proposed a value-based model for user interaction design tailored for virtual museums, underscoring the necessity of addressing both technological and emotional dimensions in the creation of digital museum experiences. Their findings emphasize the significance of crafting immersive experiences that are not only technologically advanced but also emotionally impactful, thereby ensuring that visitors engage in meaningful and memorable interactions with the exhibited content.

3. Emotional and educational impact of digital museums

3.1. The role of emotions in museum experiences

The emotional resonance of museum visits plays a pivotal role in assessing their overall effectiveness. Museums serve not merely as venues for passive education; they are dynamic spaces that elicit emotions, spark curiosity, and foster contemplation. The advent of digital technologies, especially virtual reality (VR) and augmented reality (AR), has been demonstrated to amplify these emotional reactions by offering immersive and interactive experiences that profoundly connect with visitors. Sylaiou et al. [7] investigated the role of avatars as narrative agents in virtual museum settings, emphasizing how emotionally charged stories can deepen visitor engagement. Their findings indicated that when avatars are skillfully incorporated into VR environments, they can lead visitors through exhibitions in a manner that feels intimate and captivating, thereby forging stronger emotional ties to the material presented. This method proves particularly advantageous in virtual contexts where conventional interaction methods, such as guided tours or tangible displays, are unfeasible.

Additionally, research conducted by Marín-Morales et al. [2] examined the psychophysiological responses of visitors in both physical and immersive-virtual settings. The results revealed that VR can effectively mimic the emotional experiences associated with actual museum visits, indicating that digital technologies possess the capacity to elicit comparable emotional reactions, even in the absence of physical objects. This finding is especially significant for museums aiming to broaden their audience through virtual exhibitions, as it implies that digital experiences can be equally impactful as their physical counterparts.

3.2. Educational outcomes and interactive learning

Beyond their emotional resonance, digital museums possess the capacity to markedly improve educational outcomes. By offering interactive and captivating content, these technologies can promote deeper learning and render intricate subjects more approachable for a wider audience. Daniela [8] investigated the function of virtual museums as educational agents, underscoring their capability to deliver personalized learning experiences tailored to the distinct needs and preferences of visitors. The research indicated that virtual museums could create a more flexible and adaptable educational environment than conventional museums, thereby enhancing their effectiveness for educational purposes.

Additionally, the research conducted by Tserklevych et al. [9] emphasizes the role of virtual museum environments as pioneering resources for student research. The authors contend that virtual museums furnish a distinctive platform for students to interact with historical material in an engaging and immersive manner, which fosters improved information retention and a more profound comprehension of the subject matter. This is especially pertinent in the realm of higher education, where digital technologies can complement traditional pedagogical approaches and offer students innovative avenues for engaging with complex historical and cultural narratives.

4. User experience in digital museums

4.1. Usability and accessibility

The effectiveness of digital museum experiences is significantly influenced by their usability and accessibility. As museums progressively incorporate digital technologies into their services, it becomes essential to guarantee that these technologies are user-friendly and accessible to a diverse audience. Othman et al. [10] performed a usability assessment of a virtual reality smartphone application tailored for a living museum. Their results underscored the necessity of user-centric interfaces and intuitive design to facilitate a positive interaction for visitors with the technology. The research also highlighted the importance of accommodating the varied needs of museumgoers, especially those who may lack familiarity with digital tools.

In a similar vein, the study by Kabassi et al. [11] evaluating virtual museum tours in Italy emphasizes the critical role of accessibility in digital museum experiences. The authors discovered that, although virtual tours can offer significant educational value, their effectiveness is frequently hindered by technical challenges, such as inadequate navigation and incompatibility with various devices. To mitigate these issues, the study advocates for the establishment of standardized guidelines for the design and execution of virtual tours, ensuring accessibility for all visitors, irrespective of their technological proficiency.

4.2. Personalization and interactivity

A significant benefit of digital museums lies in their capacity to provide personalized experiences tailored to the unique preferences and requirements of each visitor. By leveraging artificial intelligence and machine learning technologies, these institutions can develop individualized tours and suggestions, thereby enriching the overall experience for attendees. Research conducted by Zou et al. [6] proposed a value-oriented framework for user interaction design in virtual museums, underscoring the critical role of personalization in fostering meaningful and engaging encounters. The authors contend that by aligning content with the specific interests and inclinations of visitors, museums can amplify emotional engagement, ensuring that the experience is both pleasurable and informative. Furthermore, interactivity constitutes an essential element of the digital museum experience.

The investigation by Hammady et al. [4] regarding the acceptance of mixed reality technologies within museums emphasizes the significance of interactivity in crafting engaging and unforgettable experiences. Their findings indicate that visitors value the opportunity to engage with digital content, whether through augmented reality applications that provide additional information on physical displays or virtual reality settings that facilitate exploration and discovery.

5. The role of mobile applications in enhancing museum experiences

5.1. The rise of mobile museum apps

The widespread adoption of smartphones and mobile devices has catalyzed the creation of numerous mobile applications aimed at enriching the museum experience. These applications encompass a

diverse array of functionalities, including audio guides, interactive maps, augmented reality overlays, and virtual tours, thereby offering visitors innovative methods to engage with museum content. Research conducted by Siang et al. [3] on the implementation of mobile augmented reality applications within museums underscores the capacity of these technologies to enhance user interaction with tangible exhibits. Their findings indicate that mobile applications can deliver supplementary layers of information and context, thereby augmenting the visitor experience and rendering museum content more accessible. This aspect is particularly crucial in the context of temporary or traveling exhibitions, where spatial constraints often limit the amount of information that can be presented on-site.

Furthermore, the article by Teslyuk et al. [12] emphasizes the significance of the digital transformation of museums and the necessity for these institutions to adapt to the demands of the contemporary information society. The application developed in their study is noted for its flexibility and modular architecture, which accommodates the unique characteristics of various exhibits and enhances user experience. Consequently, the mobile guide application emerges as a potent instrument for the preservation of historical heritage and the attraction of new audiences. A review of current offerings reveals a plethora of platforms and applications available for museums, such as izi.TRAVEL and Google Arts and Culture, which provide audio guides and virtual tours. These solutions significantly enhance the quality of museum tours and facilitate access to high-resolution images and detailed information regarding artworks.

5.2. The future of mobile museum apps

With the ever-changing mobile technology advancements there is always the possibility of a shift in the approach of mobile applications in the improvement of the museums. Advanced advancements in activities such as artificial intelligence and machine learning are likely to take personalisation to even higher levels where changes can be made to reflect a visitor's interest profile in real-time for a museum. Additionally, the combination of both AR and VR might offer new use cases in the domain of mobile apps that would allow for revitalising entertaining forms of education when visiting museums. For instance, people could use smartphones and applications to get a real-life experience of historical monuments, art galleries, or and be able to share stories as well.

Nevertheless, access and inclusion also become an issue every time concerning these mobile museum apps that millions of people are using. As highlighted by Othman et al. [10], it is important to ensure that the technologies that are being developed are universal and inclusive and more so for those who are not savvy in using the available digital technologies, such as mobile devices and those with a disability. This shall entail continued study and innovation to guarantee that the mobile museum APPs are not only effective and useful, but also easy to use to all the customers.

5.3. Integration of mobile applications in museum experiences

The integration of mobile applications into museum experiences has become increasingly prevalent, offering visitors enhanced engagement and personalized learning opportunities. For instance, Fonseka (2022) conducted a comprehensive literature review on museum guide mobile applications, highlighting their role in providing multilingual support, audio guides, and interactive content to cater to diverse visitor needs. The study emphasizes that such applications can alleviate challenges faced by visitors, such as language barriers and the need for personalized information, thereby enriching the overall museum experience [13].

Moreover, the development of mobile applications tailored to specific cultural contexts has shown promising results. For example, Wimalasuriya and Kapukotuwa (2021) explored the use of augmented reality (AR)-enabled mobile apps to enhance value-based interpretation at cultural world heritage sites in Sri Lanka. Their research suggests that incorporating AR features, such as virtual

reconstructions and interactive guides, can significantly improve visitor engagement and understanding of cultural heritage [14].

Additionally, the implementation of mobile augmented reality systems, like the Mobile Augmented Reality Touring System (M.A.R.T.S), has been studied for their impact on visitors' learning experiences. Ghouaiel et al. (2017) found that such systems can transform the traditional museum visit by providing immersive and interactive content, thereby enhancing both the sensitive and analytical engagement of visitors with the exhibits [15].

These studies collectively underscore the potential of mobile applications to revolutionize museum experiences by making them more accessible, interactive, and tailored to individual visitor preferences. As technology continues to evolve, further research into the design and implementation of such applications will be crucial in shaping the future of digital museums.

6. Conceptual models and frameworks for digital museums

6.1. Designing effective digital museum experiences

There is a comprehensive process of designing the digital museum experiences in which the technological and human aspects must be considered. For the concepts to be useful and relevant in the creation of appropriate experiences, museums have to incorporate conceptual models and frameworks for the use of digital commodities. Further, Margetis et al. [5] suggested the conceptual design for the "X-Reality Museums," where the different forms of XR are incorporated into a single system. This model also underlines the necessity to make the narrative of the physical and digital environment integrated, so that there can be no confusion, or shift in the perception of the visitor when they transition from one environment to another.

Zou et al. [6] proposed a value-added model for virtual museum user interface design based on the user's psychological reactions. Using case studies, the authors state that design should consider the systems' technological affordances and the sentiments elicited by the sites. This has the advantage of focusing on the need to develop experiences that are as technological as they are sentimental.

6.2. Challenges and opportunities in digital museum design

Some of the issues that arise when designing digital experiences in museums also come with it, especially when it comes to creativity and utility and user limitation and preference. When museums add digitization to their portfolios, complex questions related to the application of HCI principles, accessibility or rationality of exhibiting multimedia artefacts instead of physical ones emerge. Another important problem highlighted in the literature is the consideration of how to make it easy for all visitors to engage with the sponsoring organizations in new worlds in which visitors are surrounded by digital experiences regardless of their computing literacy or previous experience of digital media. As pointed out by Kabassi et al. [11], this demands the setting of industry rules guiding the design and presentation of the digital content to enable access as well as ease of use.

Authenticity is another problem in the context of implementation of the presented elements in the digital environment. With the focus on new technologies and reliance on the representation of pedagogical experiences, such as, particularly with the advent of the use of new media, it is possible that the use of technology that recreates the original artifacts and their setting can cause the synthesis to diminish the meaning of the artifacts. This is especially important in the sphere of virtual museums when such indicators as interesting informative originals are negotiated in the context of absent physical objects. To tackle this matter, Zou et al. [6] propose that museums should consider value-based approach to design in which the integrity and the value of messages being communicated are closely preserved in digital media while exploiting the advantages of the technology.

However, the application of digital technology into museum design is not without its fair share of challenges as listed above, but it is also a domain full of creativity and possibilities. In this way, incorporating new technologies and trying out new approaches to interacting with exhibit, museums can create rather informative and engaging as well as emotionally moving experiences. As a result, the potential for narrative, pedagogy, and participation expands to new domains, leading to new appeal for museums and sustained relationship with the public.

7. Conclusion and future directions

Digital museums represent an emerging and transformative paradigm that reimagines the nature of traditional museums and how society engages with cultural heritage. With the integration of immersive technologies such as Virtual Reality (VR), Augmented Reality (AR), and Extended Reality (XR), the role of museums has expanded beyond the physical boundaries of their buildings. These tools now allow visitors to explore collections remotely, interact with exhibits in meaningful ways, and engage in narratives that are both informative and emotionally resonant. As a result, digital museums are not only preserving cultural assets but also reinventing how these assets are presented and understood by the public.

This shift toward immersive and interactive museum experiences has opened up new educational opportunities, increased accessibility for broader audiences, and contributed to more personalized and inclusive learning environments. At the same time, these innovations present a series of challenges that must be acknowledged and addressed. Issues such as the digital divide, the complexity of user interfaces, the emotional and cognitive impact of virtual content, and the sustainability of digital infrastructure raise important questions for curators, designers, and technologists alike. Museums must ensure that their adoption of technology is guided by clear objectives, ethical considerations, and a commitment to maintaining the integrity of cultural content.

Furthermore, the integration of digital technology should not replace traditional museum experiences but rather enhance them. It is essential to strike a balance between innovation and authenticity, allowing technology to serve as a bridge between the past and the future, rather than a barrier. This requires museums to take a proactive role in research and development, collaborating with experts from various disciplines, including computer science, education, design, and psychology. Such collaboration can help ensure that immersive technologies are applied thoughtfully and creatively to amplify the museum's mission and enrich the visitor experience.

Looking ahead, future research in the field of digital museums should focus on several key areas. These include the development of new conceptual models that integrate immersive technologies into curatorial practice, the creation of user-centered content that adapts to diverse learning styles, and the evaluation of long-term user engagement and emotional impact. Additionally, museums should explore innovative methods for storytelling that blend factual information with artistic expression, thereby offering visitors not just knowledge, but also inspiration and emotional connection.

In conclusion, digital museums hold immense potential to transform how we experience and interpret culture, art, and history. By embracing technology with intention and care, and by fostering a spirit of interdisciplinary collaboration, museums can become more dynamic, inclusive, and emotionally engaging spaces. These evolving institutions have the power to not only inform and educate but also to move and inspire — offering audiences around the world the opportunity to experience culture in new and unforgettable ways.

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Declaration on Generative AI

The authors have not employed any Generative AI tools.

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