Interactive Technology and Augmented Reality in Museums: A Survey

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Abstract

This survey explores the transformative impact of interactive technology and augmented reality (AR) in museums, highlighting their role in enhancing the preservation and presentation of cultural heritage. The integration of AR and interactive technologies has revolutionized traditional museum experiences by creating immersive environments that engage diverse audiences. Through examining current applications, such as virtual tours and 3D digitization techniques, the survey underscores how these innovations facilitate deeper connections with cultural artifacts and improve educational outcomes. The incorporation of artificial intelligence within AR systems further personalizes visitor experiences, enhancing user interaction and engagement. However, the adoption of these technologies faces challenges, including technical, financial, and ethical considerations, which necessitate strategic planning and interdisciplinary collaborations. The survey also identifies future research directions, emphasizing the need for user-centric design and accessibility to ensure inclusive and impactful museum experiences. By leveraging AR and interactive technologies, museums can dynamically preserve cultural heritage, offering enriched educational experiences that connect visitors with historical narratives in novel ways.

1 Introduction

1.1 Emergence of Interactive Technology and AR in Museums

The integration of interactive technology and augmented reality (AR) in museums represents a significant transformation in cultural heritage presentation and audience engagement. This evolution arises from the need to capture audience interest in a digital age where traditional exhibits compete with modern multimedia experiences [1]. AR technologies facilitate immersive experiences that merge digital and physical realms, offering innovative interaction and engagement opportunities [2].

Technologies such as hapto-visual and auditory rendering enhance virtual immersion, allowing authentic interactions with cultural artifacts [3]. These advancements address prior limitations by providing tangible feedback, thus improving VR-based object inspection and creating more engaging cultural heritage experiences [4]. The use of Optical See-through Augmented Reality (OST AR) has also been explored to improve interactions with virtual objects, overcoming constraints of traditional methods reliant on controllers or hand gestures [5].

The incorporation of artificial intelligence (AI) within AR systems further enhances user interactions by enabling personalized and dynamic experiences [6]. This synergy exemplifies a broader trend toward leveraging digital innovations to enhance situational awareness and digital displays in museums [7]. Collaborative AR applications, such as the Blocks application, democratize AR creation, allowing users to co-create and interact with persistent structures in their physical environments [8].

As museums increasingly adopt these technologies, they not only preserve cultural heritage but also transform into interactive learning environments that provide new engagement and educational

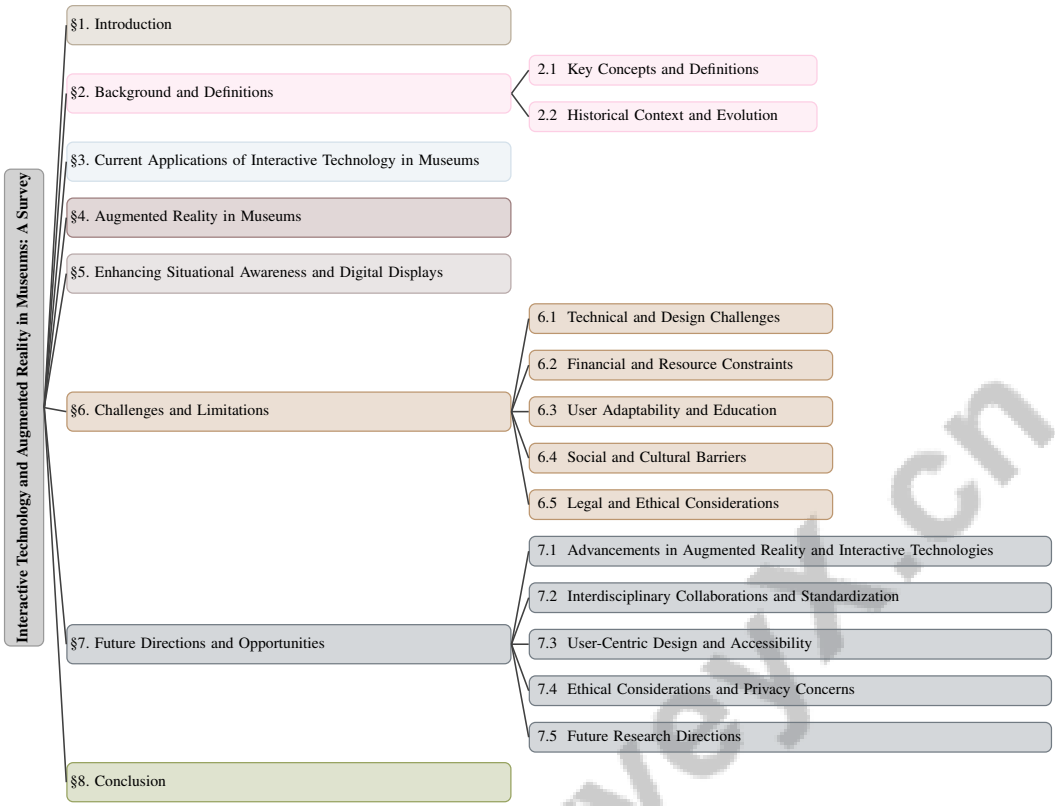


Figure 1: chapter structure

opportunities. Effective data visualization on large interactive displays, despite challenges related to perception and data density, showcases AR's potential to enrich visitor experiences [9]. These developments underscore the growing adoption of interactive technology and AR in the museum sector, highlighting their role in redefining the experience and appreciation of cultural heritage. Furthermore, classification challenges in VR and AR applications, as noted by [10], emphasize the necessity for a structured approach to understanding these technologies in educational contexts, while the preferences of older adults in VR museum visits, explored by [11], reflect the sector's expanding technological landscape.

1.2 Relevance and Importance for Cultural Heritage Preservation

The integration of interactive technology and AR in museums is crucial for the preservation and presentation of cultural heritage, offering innovative solutions to protect and disseminate cultural knowledge. AR facilitates immersive experiences that allow users to explore and interact with cultural artifacts and historical narratives, thereby enhancing understanding and appreciation [12]. This capability is vital for engaging audiences with the historical and artistic significance of cultural artifacts, such as murals, through interactive and accessible means [13].

Interactive technologies convert museum spaces into dynamic educational environments. For instance, VR experiences, such as those developed for exploring the Aipan art form, provide engaging platforms for learning about artistic techniques and cultural significance [14]. Incorporating actors in VR storytelling enhances user experience and improves the educational value of virtual cultural heritage applications [15]. Moreover, AR is perceived as adding significant value to the museum experience, with benefits including increased visitor engagement, improved educational outcomes, and enhanced cultural storytelling [16].

The necessity for digital preservation is underscored by the risks that cultural artifacts face, emphasizing the importance of these technologies in safeguarding both tangible and intangible cultural heritage [17]. The development of interactive visualization tools, such as MuseumViz, has shown

significant improvements in user experience for browsing cultural heritage artifacts, illustrating the effectiveness of interactive technologies in enhancing cultural heritage accessibility [18].

Sound, as explored by Audible Artefact Research (AAR), highlights its significance for cultural heritage preservation, offering novel auditory experiences that complement visual interactions [19]. However, the adoption of AR technologies in consumer markets is often limited by high development costs and the need for specialized hardware [20]. Despite these challenges, the conceptual shift towards understanding AR as a medium that enables simultaneous experiences of physical and digital spaces marks a critical improvement in its application [21].

The incorporation of haptic feedback in virtual reality environments significantly enhances user interaction with fragile artifacts that cannot be physically handled, underscoring the transformative impact of these technologies in preserving cultural heritage [4]. Tailored VR experiences for older adults emphasize the importance of enhancing engagement and accessibility in cultural heritage preservation, ensuring diverse audiences benefit from these technological advancements [11]. Collectively, these developments underscore the transformative impact of interactive technology and AR in preserving cultural heritage, ensuring its dynamic presentation to engage and educate diverse audiences.

1.3 Structure of the Survey

This survey is organized into several key sections, each addressing distinct aspects of the integration of interactive technology and augmented reality (AR) in museums. The initial section introduces the topic, highlighting the increasing use of these technologies in enhancing situational awareness and digital displays for cultural heritage preservation, setting the stage for understanding their transformative impact in the museum sector.

Following the introduction, the survey delves into the emergence of interactive technology and AR in museums, exploring how these innovations have become integral to modern museum practices, supported by research that underscores the shift toward digital experiences.

The subsequent section examines the relevance and importance of these technologies in cultural heritage preservation, showcasing their role in creating immersive and educational experiences that facilitate deeper engagement with cultural artifacts.

An in-depth exploration of essential concepts and definitions related to augmented, virtual, and mixed reality technologies follows, placing them within a historical framework that traces their evolution and adaptation in museum environments. This context highlights how these immersive technologies have transformed the presentation and engagement with cultural heritage, enabling audiences to interact with artifacts in innovative ways [22, 23, 24, 25, 26].

The current applications of interactive technology in museums are extensively examined, emphasizing their role in enhancing visitor engagement and educational experiences. This includes the use of interactive exhibits, digital storytelling, and advanced 3D visualization techniques, which facilitate immersive learning and address challenges such as content comprehension and audience interaction. For instance, implementing guiding questions in virtual museums effectively encourages visitor exploration and improves understanding of complex information, while interactive digital storytelling serves as a dynamic medium for presenting cultural heritage, fostering deeper connections between audiences and educational content [25, 27].

Next, the role of augmented reality in museums is discussed, focusing on its potential to create immersive learning experiences and its educational impact. The significance of user experience (UX) and design in AR applications is critically analyzed, highlighting the necessity for thorough evaluation of user interactions to enhance effectiveness and adoption across various domains, including education and social activism. This evaluation is essential for identifying user perceptions and improving existing AR systems while addressing challenges in creating immersive experiences that align with users' needs and expectations [28, 29, 30, 31, 32].

The survey delves into the role of interactive technology and AR in enhancing situational awareness and digital displays, highlighting various visualization techniques and spatial interaction methods. This includes integrating printed data visualizations with AR, allowing for dynamic updates and intuitive user engagement through tangible interactions like touch and tilt. Additionally, the survey examines how large interactive displays combined with personal AR can facilitate data exploration

and analysis by providing personalized views and minimizing distractions, ultimately improving understanding of complex data sets [28, 33, 9].

The implementation of new technologies in museums faces various challenges and limitations, including technical issues related to integration and user experience, financial constraints impacting budget allocation, user adaptability to novel interfaces, and social and cultural factors influencing acceptance. Legal and ethical considerations, particularly concerning the safeguarding of intangible cultural heritage, must also be addressed, as highlighted in recent research on immersive technologies and their application in cultural preservation. These multifaceted challenges underscore the need for a comprehensive approach to effectively harness these technologies for enhancing visitor engagement and cultural knowledge transmission [23, 34, 35].

Finally, the survey explores future directions and opportunities, discussing advancements in technology, interdisciplinary collaborations, user-centric design, and areas for future research. The conclusion integrates essential insights from recent research on the role of advanced technologies, such as multimodal large language models and linked data frameworks, in revolutionizing museum experiences and safeguarding cultural heritage. It emphasizes how these innovations facilitate more effective search and discovery of visual collections, enhance usability through standardized data publication, and support interactive digital storytelling in educational contexts. By addressing ethical considerations and interoperability challenges, these technologies enrich user engagement and promote collaborative efforts in preserving and sharing cultural resources across diverse platforms and institutions [22, 27, 36].The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Key Concepts and Definitions

Augmented Reality (AR) and Virtual Reality (VR) are pivotal in transforming museum experiences by creating immersive environments that enhance visitor interaction. AR overlays digital elements onto the real world, enriching user perception and interaction with cultural artifacts, while VR offers entirely virtual spaces for exploration [9]. These technologies are essential for developing interactive experiences that deepen connections with cultural heritage and improve educational outcomes [10]. True AR seamlessly integrates real and virtual elements, enhancing realism and interactivity in cultural heritage experiences [7].

Mobile Augmented Reality (MAR) enhances museum experiences through user-centric designs that deliver accessible and informative content, significantly boosting visitor engagement [6]. Effective AR design involves selecting physical anchors based on historical significance and technical feasibility [37]. Moreover, integrating AR with big data enriches user engagement by providing contextual information [38].

Interactive technology in museums addresses the challenge of communicating complex datasets, thus enhancing the educational value of exhibits [39]. Haptic interaction adds a tactile dimension to experiencing cultural artifacts [5]. Using AR Head Mounted Displays (HMDs) and considering Field of View (FoV) are crucial for effective user experiences despite technological limitations [11].

Underwater Augmented Reality (UWAR) illustrates AR's versatility by visualizing submerged archaeological sites through hybrid tracking techniques, enhancing appreciation of underwater cultural heritage [8]. This highlights AR's potential across diverse museum settings [39].

Preserving 3D digital data in cultural heritage is critical, especially given technological obsolescence [7]. Visualizing 3D scanned objects on 2D screens often reduces engagement, particularly for artifacts not physically accessible [11]. AR technologies are classified into marker-based, markerless, projection-based, and overlap-based methods [10]. Integrating digital twins and IoT devices into visitor experiences enhances cultural heritage tourism, offering new engagement opportunities [9]. Interoperability among cultural heritage resources and linked data usability are essential for enhancing user engagement [39].

These technologies transform visitor experiences by introducing innovative interaction and learning methods that integrate physical and digital realms. Insights from applied psychology and neuroaesthetics enhance user engagement, shifting public perception from consumption to valuing cultural

artifacts. Interactive features, such as guiding questions and multimodal interactions, improve comprehension and engagement in virtual museums [40, 25, 41].

2.2 Historical Context and Evolution

The evolution of interactive technology and AR in museums marks a shift from static displays to dynamic, immersive experiences. Initially reliant on traditional methods, museums have embraced digital technologies to integrate hybrid narratives, enhancing visitor engagement [27]. The transition from VR to AR has been key in improving accessibility and broadening historical narrative engagement [11].

Early digitization methods focused on visible surfaces, limiting engagement with cultural artifacts [42]. This necessitated sophisticated approaches for creating digital replicas, addressing issues like domain shifts when applying models trained on natural images to artworks [37]. The historical context of digital tools in museums highlights the complexity of UI/UX adaptation required for cross-reality applications [7].

The evolution of visualization techniques and collaborative environments has shaped AR development in museums, overcoming challenges in communication and understanding [10]. Historical design considerations for older adults reflect a trend towards inclusivity and accessibility [11].

Despite the rise of online museums, limited engagement persists due to ineffective display methods [9]. This is compounded by risks associated with immersive technologies in cultural heritage contexts, necessitating careful consideration of art and cultural artifacts' unique characteristics [37]. Integrating physical artifacts with digital environments enriches visitor experiences [39].

Innovative approaches, such as using Wi-Fi signals for positioning, enhance accessibility by allowing smartphone use instead of specialized hardware [7]. The survey organizes methodologies into fields like computer science, visual arts, and human-computer interaction to enhance user engagement with cultural heritage artifacts [27]. It also discusses AR's application in cultural heritage tourism, particularly in small museums facing unique challenges [9].

The historical trajectory of interactive technology and AR in museums reflects efforts to enhance visitor engagement and educational experiences. Hybrid narratives and mobile and extended reality technologies have transformed cultural heritage preservation and presentation. These advancements enhance artifact immersion and create innovative engagement and education avenues within diverse museum contexts. Interactive digital storytelling and mobile tools, like the Narralive Storyboard Editor and Mobile Player app, facilitate creative expression and research, while guiding questions in virtual museums improve comprehension and interaction [43, 25, 26, 27].

3 Current Applications of Interactive Technology in Museums

Examining the transformative impact of interactive technology in museums reveals its significant role in enhancing visitor engagement and educational outcomes. This section explores various technologies employed in museum exhibits, illustrating their contribution to the evolving landscape of museum experiences and their facilitation of deeper connections between audiences and cultural artifacts. As depicted in Figure 2, the current applications of interactive technology in museums can be categorized into three main areas: Interactive Technologies in Museum Exhibits, Interactive Digital Storytelling, and 3D Digitization and Visualization Techniques. Each of these areas showcases a range of technologies, tools, and methods that not only enhance visitor engagement and educational outcomes but also contribute to the preservation of cultural heritage. The figure exemplifies the transformative impact of these technologies in creating immersive and participatory museum experiences, reinforcing the argument for their integration into contemporary museum practices. Additionally, Table 2 presents a comparative overview of the applications of interactive technologies in museum settings, highlighting their engagement strategies, technological tools, and educational impacts.

3.1 Interactive Technologies in Museum Exhibits

Interactive technologies have revolutionized museum exhibits, transforming traditional viewing into participatory and educational experiences. Technologies such as touchscreens, virtual tours, and augmented reality (AR) are crucial in fostering deeper engagement with cultural artifacts. The

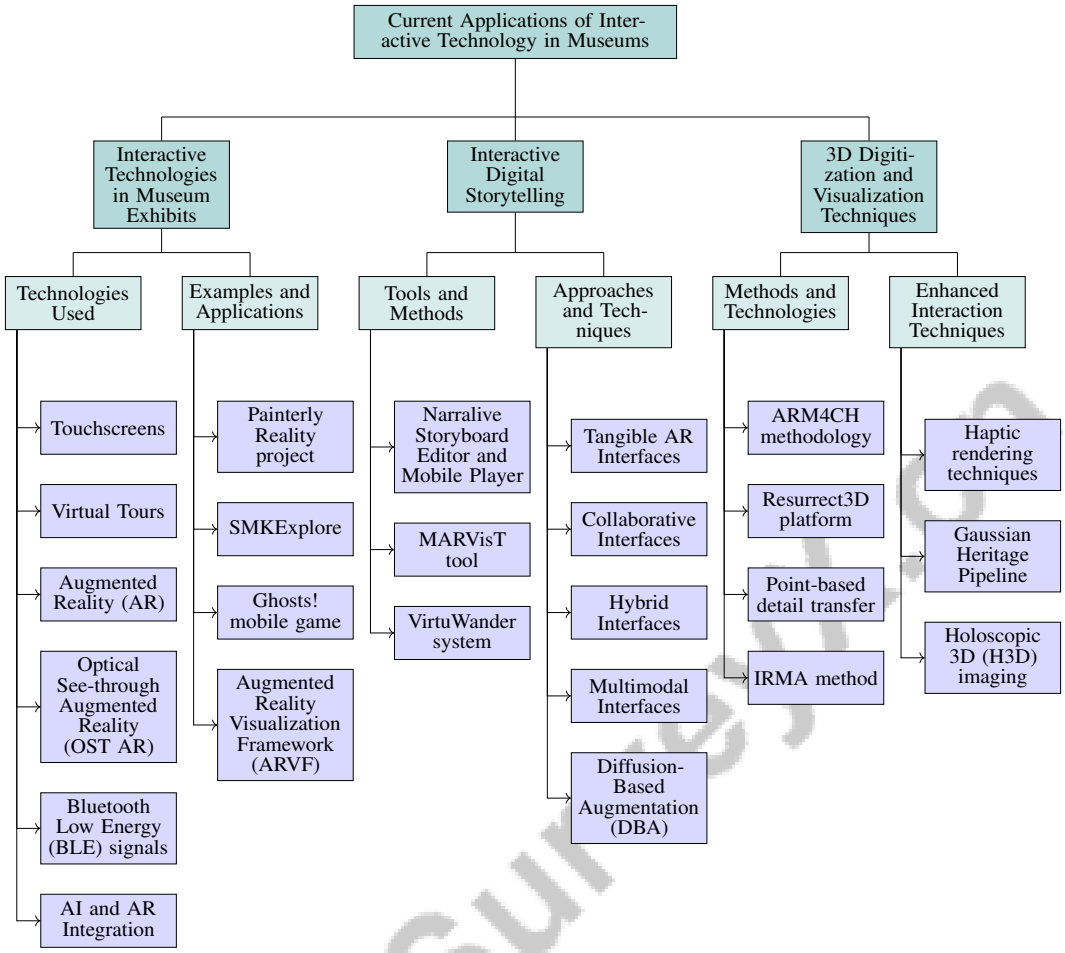


Figure 2: This figure illustrates the current applications of interactive technology in museums, highlighting three main areas: Interactive Technologies in Museum Exhibits, Interactive Digital Storytelling, and 3D Digitization and Visualization Techniques. Each area showcases various technologies, tools, and methods that enhance visitor engagement, educational outcomes, and the preservation of cultural heritage. The figure exemplifies the transformative impact of these technologies in creating immersive and participatory museum experiences.

Method Name	Technological Integration	User Engagement	Educational Enhancement
PR[1]	Augmented Reality	Bodily Engagement	Interactive Technologies
ATPO[5]	Augmented Reality	Intuitive Manipulation	Interactive Technologies
N/A[38]	Interactive Web Application	Interactive Interface Exploration	Innovative Learning Platforms
N/A[44]	Ble Technology	Interactive Experience	Innovative Learning Platforms
ARVF[9]	Augmented Reality	Enhanced Interaction Techniques	Innovative Learning Platforms
TCM[10]	Virtual Reality Applications	User Interaction	Educational Objectives Taxonomy

Table 1: Categorization of interactive technologies utilized in museum exhibits, detailing their technological integration, user engagement methodologies, and contributions to educational enhancement. This table highlights various methods such as Augmented Reality and Virtual Reality applications, showcasing their roles in transforming traditional museum experiences into interactive learning platforms.

Painterly Reality project exemplifies this by enabling real-time audience interaction with paintings through a three-dimensional AR environment, enhancing immersion [1].

Table 1 presents a comprehensive overview of interactive technologies implemented in museum exhibits, emphasizing their integration, user engagement strategies, and educational enhancements. Figure 3 illustrates the categorization of interactive technologies in museum exhibits, highlighting key approaches such as Augmented Reality, Virtual Tours, and Location-based Applications, with

specific examples like Painterly Reality and the Ghosts! game. Optical See-through Augmented Reality (OST AR) utilizes abstract tangible proxies, allowing users to interact with virtual content using physical objects, thus enriching user interaction with exhibits [5]. Virtual tours, enhanced by digital twin creation methods like photogrammetry, extend the reach of museum collections by capturing both physical and digital assets [38]. Applications such as SMKExplore leverage object detection data to personalize the visitor experience by enabling exploration based on detected objects [38].

Innovative approaches, like using Bluetooth Low Energy (BLE) signals in location-based applications, exemplified by the mobile game Ghosts!, introduce new visitor engagement methods by creating interactive museum experiences [44]. The Augmented Reality Visualization Framework (ARVF) combines large interactive displays with personal AR head-mounted displays to enhance data visualization and visitor engagement [9]. The integration of AI and AR in exhibits further emphasizes the importance of interface design in enhancing user awareness and engagement [6].

Challenges remain in optimizing user interactions within shared immersive environments. Developing standardized metrics for evaluating AR user experience is essential to enhance museums' educational missions [10]. Comparative analyses of VR museum designs highlight their effectiveness in engaging older adults through multi-sensory interactions, emphasizing inclusivity in technology applications [11]. These technologies enrich visitor experiences and support museums' educational objectives by providing innovative learning and exploration platforms.

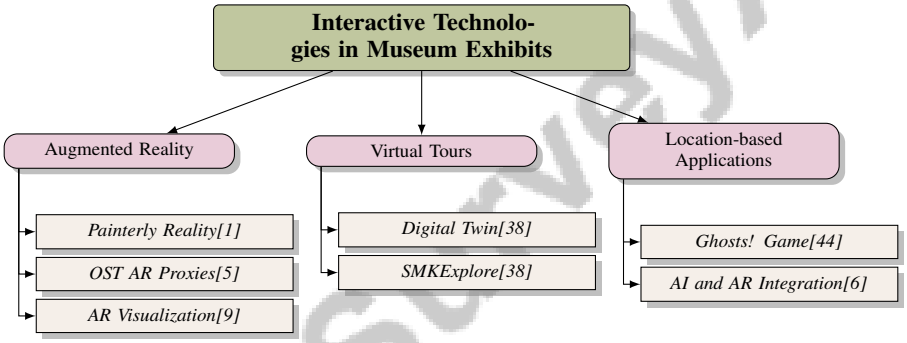


Figure 3: This figure illustrates the categorization of interactive technologies in museum exhibits, highlighting key approaches such as Augmented Reality, Virtual Tours, and Location-based Applications, with specific examples like Painterly Reality and Ghosts! Game.

3.2 Interactive Digital Storytelling

Interactive Digital Storytelling (IDS) in museums engages visitors by integrating narratives into immersive experiences. Tools like the Narralive Storyboard Editor and Mobile Player allow for the creation and experience of interactive digital narratives, enhancing visitor engagement [43]. AR integration within IDS transforms static displays into interactive learning environments, particularly benefiting educational experiences for schoolchildren [45]. The MARVisT tool exemplifies this by enabling AR glyph-based visualizations, enhancing engagement through interactive storytelling [46].

Immersive simulations in digital planetariums and virtual museums offer unique storytelling forms, combining visual and narrative elements to provide comprehensive educational experiences [47]. IDS's ability to increase learner motivation and engagement highlights its potential to revolutionize museum education [27]. Interactive user interfaces and data acquisition technologies support IDS by facilitating multimodal interactions, allowing for responsive and contextually aware storytelling [34]. The VirtuWander system, for instance, enhances storytelling by generating responsive multimodal feedback [48].

Current IDS methods are categorized into tangible AR interfaces, collaborative interfaces, hybrid interfaces, and multimodal interfaces, each offering unique opportunities for enhancing visitor interaction [49]. Data augmentation techniques, like Diffusion-Based Augmentation (DBA), enrich interactive narratives while maintaining semantic integrity, providing a richer storytelling experience [37].

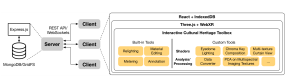
3.3 3D Digitization and Visualization Techniques

3D digitization and visualization techniques are crucial for creating engaging museum displays, offering immersive and interactive experiences with cultural heritage artifacts. The ARM4CH methodology utilizes cooperative robots and UAVs for optimized scanning operations, ensuring comprehensive 3D digitization of cultural sites [50]. This enhances precision and efficiency in capturing detailed 3D models, supporting digital preservation and interactive display.

The Resurrect3D platform provides tools for relighting, material editing, and custom tool development, allowing dynamic customization of 3D models to enhance visual storytelling [51]. Point-based detail transfer methods, like those used in the digital reconstruction of Elmina Castle, create high-quality 3D models from point clouds, offering accurate representations of historical structures [52]. The IRMA method uses non-destructive techniques for visualizing fragile archaeological objects, aligning with the demand for conservation-friendly digitization practices [42].

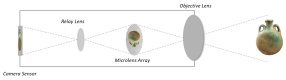
Haptic rendering techniques, such as the Combined Hapto-Visual and Auditory Rendering Framework (CHVAR), integrate haptic feedback, visual depth rendering, and audio cues to enhance interaction with 3D objects [3]. The Gaussian Heritage Pipeline method generates instance-aware 3D models from RGB images, facilitating engaging displays by leveraging RGB imagery's visual richness [39]. Holoscopic 3D (H3D) imaging efficiently captures detailed 3D images, reducing time and costs and aiding rapid digitization for virtual displays [53].

These techniques enhance museums' abilities to develop engaging displays that integrate physical and digital experiences. By utilizing interactive guiding questions, digital storytelling, and advanced multimodal language models, museums can improve visitor engagement and comprehension, making cultural artifacts more accessible and enriching. This approach fosters deeper connections with content and aligns with user-centered design concepts, transforming the visitor experience into one emphasizing active participation and personal valuation of cultural heritage [25, 22, 41, 27].



(a) Interactive Cultural Heritage Toolbox[51]

(b) Augmented Reality in Education and Business: A Comparative Study[54]



(c) Optical System for High-Resolution Imaging[53]

Figure 4: Examples of 3D Digitization and Visualization Techniques

As shown in Figure 4, museums increasingly adopt interactive technology to enhance visitor engagement and education. The application of 3D digitization and visualization techniques is exemplified in the figure, showcasing three interconnected applications in cultural and educational settings. The "Interactive Cultural Heritage Toolbox" integrates web technologies with Three.js and WebXR, offering a versatile platform for customization. The "Augmented Reality in Education and Business" highlights AR's transformative potential, enhancing printed materials with dynamic infographics. The "Optical System for High-Resolution Imaging" reveals a system capable of capturing detailed images, underscoring precision and innovation in modern exhibits. These examples illustrate interactive technology's diverse applications and benefits in preserving and presenting cultural heritage [51, 54, 53].

Feature	Interactive Technologies in Museum Exhibits	Interactive Digital Storytelling	3D Digitization and Visualization Techniques
Engagement Strategies	Participatory Experiences	Narrative Integration	Immersive Experiences
Technological Tools	Touchscreens, Ar, Ble	Narralive, Marvist	Arm4ch, Resurrect3d
Educational Impact	Enhanced Immersion	Increased Motivation	Digital Preservation

Table 2: This table provides a comparative analysis of three distinct applications of interactive technologies in museums: Interactive Technologies in Museum Exhibits, Interactive Digital Storytelling, and 3D Digitization and Visualization Techniques. It highlights key features such as engagement strategies, technological tools, and educational impact, emphasizing their roles in enhancing visitor engagement and preserving cultural heritage.

4 Augmented Reality in Museums

4.1 Augmented Reality and Experiential Learning

Augmented Reality (AR) enhances experiential learning in museums by merging digital information with physical exhibits, creating interactive experiences that improve educational outcomes [9]. AR's flexibility allows diverse physical objects to serve as proxies, expanding interactive applications and optimizing museum displays [5]. The XR Transition Manager illustrates AR's role in experiential learning by integrating AR, VR, and MR applications into a cohesive learning journey [7]. The Blocks application supports collaborative engagement with exhibits, enhancing understanding through synchronous and asynchronous interactions [8].

Innovative interaction methods, such as visual notifications paired with localized audio cues, enhance task performance and engagement, particularly for older adults [55, 11]. AR promotes inclusivity by providing accessible alternatives for users with visual impairments, democratizing access to cultural heritage [56]. Recent AR advancements foster interactive learning environments that integrate artifacts with digital content, engaging diverse audiences through interactive guiding questions and audio-augmented experiences. This approach supports active learning, collaboration, and critical thinking, enriching museums' educational missions and facilitating knowledge retention [57, 27, 58, 25, 19].

4.2 Educational Impact of AR in Museums

AR applications enhance educational outcomes in museums by creating interactive learning environments. By incorporating AR, exhibits foster deeper understanding of cultural artifacts through methods that boost engagement and learning efficiency [59]. Techniques like Pointing Line (PL) and Moving Track (MT) improve user performance and social presence in collaborative tasks [59]. AR's integration of semantic mapping, deep material learning, and SLAM technology enables realistic interactions with virtual objects, offering dynamic educational experiences [60].

AR enhances visual search efficiency with well-designed cues, improving user interaction [61]. However, careful application is necessary in high-stakes scenarios to avoid over-reliance on automation [61]. Adjustments in spatial formation for virtual humans (VHs) in AR environments enhance educational potential by maintaining stable interactions, ensuring a smooth learning experience [62]. The potential of Artificial Intelligence Generated Content (AIGC) to personalize AR experiences presents exciting educational possibilities, although challenges related to technical limitations and privacy concerns must be addressed [63].

4.3 User Experience and Design in AR Applications

User-centered design is crucial for developing effective AR applications, ensuring accessibility and engagement for diverse users. The IRMA method exemplifies this approach by facilitating natural interactions in virtual and augmented reality environments [42]. Integrating Artificial Intelligence (AI) into AR systems emphasizes human-centered design, focusing on user awareness and safety [6]. AI enhances user engagement by providing personalized interactions.

Multiple Resource Theory supports user-centered AR design, suggesting that efficient task management is achieved through notifications that minimize cognitive load [55]. Creating accessible alternatives for AR tasks is critical for inclusivity, as prototypes demonstrate the feasibility of making mobile AR applications more accessible [56]. The Collaborative Augmented Reality Interaction (CARI) framework emphasizes synchronization in collaborative AR environments, enhancing communication and interaction among users [64].

As illustrated in Figure 5, which showcases key aspects of user experience in AR applications, the integration of AR in museums enhances user experiences by merging digital content with the physical world. This figure highlights the significance of user-centered design, efficient task management, and accessibility in AR applications. The VegaAR framework enables interactive AR graph visualizations, providing dynamic tools for exploring complex data intuitively in educational settings. Furthermore, the categorization of AR apps in the App Store underscores AR's broad application spectrum, particularly in entertainment and education, emphasizing its potential to revolutionize museum exhibits by making them more interactive and accessible [54, 56].

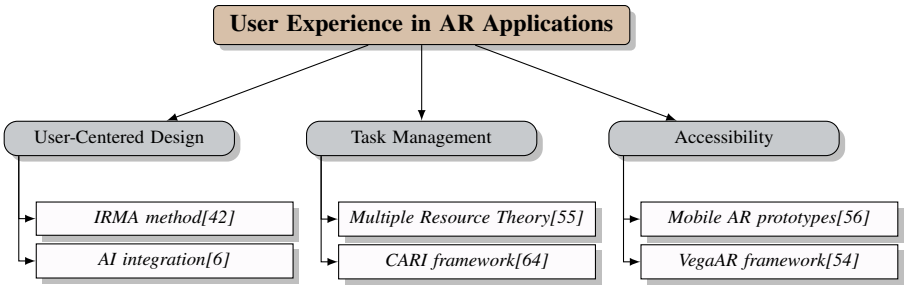


Figure 5: This figure illustrates the key aspects of user experience in AR applications, including user-centered design, efficient task management, and accessibility. It highlights the significance of integrating AI for personalized interactions, utilizing frameworks like CARI for collaborative task management, and developing accessible alternatives for mobile AR applications.

5 Enhancing Situational Awareness and Digital Displays

5.1 Visualization Techniques and User Engagement

Visualization techniques are pivotal in enhancing user engagement within museums, providing immersive experiences that cater to diverse audiences through the integration of Augmented Reality (AR) and Virtual Reality (VR) technologies. These technologies allow for innovative presentations of cultural artifacts, revealing hidden details and improving user comprehension [65]. Digital Twin Creation extends access to cultural heritage by offering interactive digital representations beyond physical spaces, while smartphones facilitate portable and shareable interactions with artworks [66].

The AR Vibration Monitoring (ARVM) method exemplifies the overlaying of real-time data, such as vibration sensor information, onto physical structures, enhancing situational awareness [67]. Techniques that blend real and virtual environments create feedback loops deepening immersion in VR experiences [40]. The Aipan VR experience connects users with cultural heritage through immersive technology [14].

AR applications enhance situational awareness by interactively displaying operational commands, providing clear guidance [68]. The Generous Interface approach facilitates exploration of photographic collections across multiple dimensions [69]. MuseumViz employs interactive visualization methods to present cultural heritage data, significantly boosting user engagement [18]. The AR Visualization Framework (ARVF) overlays personalized AR content onto existing visualizations, enhancing situational awareness [9]. Immersive technologies foster emotional connections with historical events, enhancing educational engagement [13].

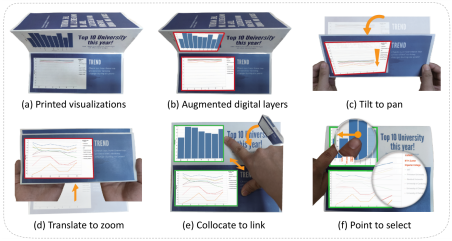
Digital technologies transform preservation efforts, creating dynamic educational environments in museums [17]. The H3D method offers a cost-effective solution for 3D digitization, broadening its applicability in cultural heritage preservation [53]. Audible Artefact Research (AAR) explores the use of sound in exhibits, enhancing emotional engagement and interpretative diversity [19].

These visualization techniques enhance user engagement by providing interactive, personalized, and emotionally impactful experiences, effectively captivating and educating diverse audiences. Environmental factors, such as crowding levels, also affect user experiences and social acceptability, underscoring their importance in museum exhibit design [70].

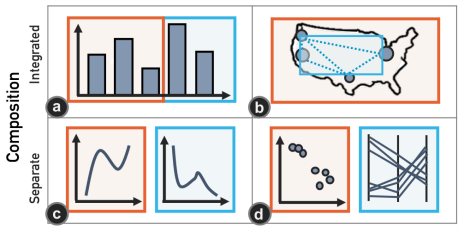
As shown in Figure 6, visualization techniques are crucial in enhancing situational awareness and user engagement within museum environments. The figure illustrates innovative methods merging traditional and digital mediums, enriching user experiences. "Augmented Paper: A Novel Approach to Interactive Paper-Based Information Display" transforms printed pages into interactive platforms with digital overlays, while "Integrated vs. Separate Composition" emphasizes the importance of visual representation and data integration in creating cohesive displays [33, 54].

5.2 Augmented Reality and Spatial Interaction

Augmented Reality (AR) significantly enhances spatial interaction in museums, providing immersive experiences that seamlessly integrate digital content with physical spaces. This technology enriches



(a) Augmented Paper: A Novel Approach to Interactive Paper-Based Information Display[33]



(b) Integrated vs. Separate Composition[54]

Figure 6: Examples of Visualization Techniques and User Engagement

museum displays through dynamic overlays of information on existing exhibits, improving visitor experiences. Utilizing existing Wi-Fi infrastructure for indoor positioning exemplifies AR's potential to facilitate spatial interaction, offering users smooth navigation within museum settings [71]. This infrastructure allows museums to deliver precise location-based content, enhancing visitor engagement and comprehension.

AR applications are designed to respect social norms regarding personal space, creating natural and conflict-free interactions, improving user satisfaction, and ensuring non-users are not disturbed by AR engagement [62]. Incorporating these design principles allows AR technologies to facilitate intuitive spatial interactions, enabling users to engage with digital content naturally and unobtrusively.

The integration of AR into museum displays fosters personalized and context-sensitive interactions, allowing visitors to explore exhibits at their own pace and according to their interests. This personalization addresses challenges such as data complexity and information overload, promoting deeper understanding and active participation [25, 9]. By employing spatial interaction techniques that adapt to individual preferences, AR transforms static displays into interactive environments, enriching engagement with cultural artifacts and historical narratives, ultimately enhancing the educational value of museum visits.

6 Challenges and Limitations

6.1 Technical and Design Challenges

The integration of interactive technology and AR in museums faces significant technical and design challenges that impact user engagement and operational efficiency. A primary technical issue is the seamless integration of virtual and real-world content, complicating the development of accessible AR applications, especially for visually impaired users [56]. Dependence on mobile devices and AR headsets introduces performance issues during real-time data visualization, affecting accessibility and inclusivity [2].

Design challenges involve creating user-centered approaches for diverse audiences. Variability in visitor engagement, influenced by surrounding exhibits and demographics, necessitates inclusive experiences [70]. However, inconsistencies in methodologies and a lack of comprehensive metrics for user experience (UX) evaluation limit the comparability and generalizability of findings [31].

The effective placement and modality of AR notifications pose additional challenges, as traditional frameworks do not adapt well to AR systems [55]. Cognitive load from switching between multiple visualizations complicates AR content perception [9]. Technical obstacles include latency and calibration issues in projection-based AR systems, affecting user experience [72]. The complexity of UI/UX adaptation for various realities presents obstacles for developers, discouraging application creation across the extended reality (XR) spectrum [7].

Challenges in spatial orientation and navigation within VR environments, especially for older adults, highlight the need for tailored solutions [11]. Potential time lag between haptic and audio rendering can detrimentally affect user experience, as shown by the Combined Hapto-Visual and Auditory Rendering Framework [3].

6.2 Financial and Resource Constraints

The adoption of interactive technology and AR in museums is constrained by financial and resource limitations, impeding implementation and sustainability. High costs associated with data storage and preservation impose a substantial financial burden, particularly on smaller organizations struggling to invest in advanced technologies without clear evidence of their value [73, 16].

Acquiring AR technologies entails considerable financial risk, as initial investments in hardware and software can be daunting for institutions with limited budgets [74]. This financial strain is compounded by a lack of professional expertise among museum staff, complicating AR integration into existing exhibits [74]. Insufficient methodological resources hinder museums' willingness to fully embrace AR solutions [74].

Innovative methods, like the Gaussian Heritage Pipeline, have been proposed to mitigate costs and streamline the digitization process, making it more feasible for resource-limited museums [39]. Despite advancements in AR technology, including cost-effective, open-source solutions for artifact visualization, financial constraints continue to inhibit widespread adoption. Many AR platforms necessitate proprietary applications that complicate user access and reduce global availability [16, 75]. Addressing these challenges requires strategic planning and collaboration among stakeholders to develop sustainable funding models and resource-sharing initiatives.

6.3 User Adaptability and Education

Integrating interactive technology and AR in museums raises challenges related to user adaptability and the necessity for comprehensive education and training. Users often face a steep learning curve in immersive environments due to technology complexity and the requirement for real-time tracking and depth data [76]. This complexity can lead to cognitive overload, particularly for those unfamiliar with AR applications, highlighting the need for targeted educational initiatives [77].

The use of publicly accessible geospatial data in AR applications introduces privacy concerns affecting user adaptability, underscoring the importance of transparent communication and education [78]. Effective user education is vital during co-design sessions involving mixed artifacts, as understanding their roles is essential for successful collaboration [79].

Adapting older adults to VR environments requires tailored education and training programs to ensure effective navigation of these technologies [11]. Challenges in remote collaboration settings, like those in applications such as Blocks, further emphasize the need for user coordination and communication, which can be enhanced through education and training [8].

Future research should explore innovative techniques, such as integrating eye gaze as a pointing mechanism, to improve user adaptability in close-range tasks within AR applications [80]. Addressing these challenges necessitates a comprehensive approach combining technological advancements with educational strategies to empower users and enhance their interactions with AR and VR technologies in museum contexts [81].

6.4 Social and Cultural Barriers

Implementing interactive technologies and AR in museums is hindered by social and cultural barriers affecting acceptance and effectiveness. A significant barrier is the complexity of implementing open standards, requiring extensive collaboration among diverse stakeholders within the museum community [36]. This complexity can lead to resistance from institutions wary of adopting new technologies without clear guidelines and frameworks for integration.

Cultural barriers play a critical role in adopting interactive technologies. Museums, traditionally seen as custodians of cultural heritage, may resist modifying established presentation and interpretation methods. Innovative approaches, like using guiding questions in virtual museums, demonstrate that engaging audiences and enhancing understanding can be achieved through interactive strategies adapting to the evolving landscape of cultural access [25, 22]. Concerns that technology may detract from the authenticity of cultural artifacts further complicate this reluctance, leading to a preference for traditional methods perceived as more respectful of cultural heritage. Engaging the community is essential to overcoming these barriers, fostering a sense of ownership and acceptance of technological innovations in the cultural sector.

The diverse demographics of museum visitors necessitate careful consideration of cultural sensitivities and inclusivity in designing interactive experiences. To ensure technologies are accessible and relevant to a broad audience, they must be developed with a deep understanding of cultural differences, particularly regarding Intangible Cultural Heritage (ICH) preservation. This involves recognizing the unique cultural expressions and practices communities identify with, as highlighted by UNESCO's cultural heritage safeguarding efforts. Integrating new technologies, like 3D visualization and interactive digital storytelling, can enhance engagement and educational value but must be carefully designed to address varying cultural perspectives and balance educational content with entertainment [23, 27]. Engaging in dialogue with diverse cultural groups is crucial to understanding their needs and preferences, ensuring that interactive technologies enhance rather than hinder the visitor experience.

To effectively address complex social and cultural barriers, a multifaceted strategy is essential. This strategy should foster collaboration among stakeholders, actively engage the community, and incorporate culturally sensitive design practices. By leveraging technologies like AR to visualize and contextualize cultural narratives and emphasizing interactive engagement methods, museums can create more inclusive and impactful initiatives that resonate with diverse audiences and promote the preservation and appreciation of intangible cultural heritage [29, 82, 23, 25, 27].

6.5 Legal and Ethical Considerations

Integrating interactive technology and AR in museums introduces legal and ethical considerations that must be navigated responsibly. User privacy is a primary concern, particularly regarding camera-based systems for tangible interaction detection, which can inadvertently capture sensitive data. Robust privacy protections and transparent user consent mechanisms are essential to safeguard personal information [83].

Deploying AR and extended reality (XR) technologies in public spaces raises ethical questions about user consent and surveillance potential [84]. Using AR head-mounted displays (HMDs) to enhance visual search performance introduces further challenges, as imperfect automation may lead to unintended consequences and ethical dilemmas [61]. Developing unobtrusive methods that encourage positive user behavior while addressing legal and ethical considerations surrounding persuasive technology is vital [85].

ARtivism, involving unsanctioned public art, highlights privacy and consent issues that must be addressed to ensure ethical compliance [86]. Moreover, integrating AI within AR systems raises ethical implications requiring interdisciplinary collaboration to address safety concerns and ensure responsible use of immersive technology [6].

Digitization and preservation of cultural heritage necessitate legal frameworks facilitating these processes while respecting cultural and intellectual property rights [17]. Current research faces limitations in data collection and participant engagement methods, highlighting the need for reliable XR hardware and ethical guidelines to ensure research integrity [87].

These legal and ethical considerations underscore the necessity for comprehensive frameworks and collaborative efforts to address the complexities of integrating interactive technologies and AR in museum settings. By prioritizing privacy, informed consent, and ethical usage, museums can leverage emerging technologies—such as immersive art installations and interactive digital experiences—to enrich visitor engagement while safeguarding personal data and upholding cultural and social responsibilities. Implementing robust privacy measures, like opt-in data collection mechanisms and enhanced security awareness, is essential for fostering a safe and enriching environment for all participants [88, 25].

7 Future Directions and Opportunities

7.1 Advancements in Augmented Reality and Interactive Technologies

Recent advancements in augmented reality (AR) and interactive technologies are poised to revolutionize museum experiences, enhancing engagement and accessibility with cultural heritage artifacts. Future developments should emphasize user-friendliness and explore emerging hardware and software trends to facilitate broader AR application adoption [20, 28]. Enhancements in real-time

interaction capabilities and new application domains will further integrate AR technologies across diverse museum contexts.

Research into Holoscopic 3D (H3D) technology for larger artifacts aims to improve depth control and image quality, offering immersive visual experiences for significant exhibits [53]. The integration of medical imaging technologies into AR applications promises new insights into historical artifacts, enhancing educational value [42]. Future investigations should explore the relationship between proxy object dimensions and the acceptable abstraction levels for virtual objects, potentially enhancing user interactions within AR environments [5]. Additionally, evaluating collaborative scenarios and sharing AR content among users can enrich the social dimension of museum visits [9].

The integration of artificial intelligence (AI) with AR systems presents a promising avenue, focusing on understanding AI-AR interaction dynamics and developing safe design practices [6]. This could facilitate personalized and context-sensitive interactions tailored to individual visitor preferences. Expanding rapid prototyping frameworks to support various SDKs and devices, and automatically adapting application features based on target realities, is critical for developing versatile AR applications [7]. Evaluating pipelines like the Gaussian Heritage Pipeline in real-world museum settings could offer insights into practical applications [39].

Future research should enhance visual cueing techniques, such as color-coding and positioning strategies, to improve user interaction and efficiency in AR environments [55]. Advancements in VR technologies tailored for older adults, including personalized content and multi-sensory feedback, are essential for ensuring inclusivity and accessibility for all museum visitors [11].

7.2 Interdisciplinary Collaborations and Standardization

Progress in interactive technology and augmented reality (AR) in museums is significantly enhanced by interdisciplinary collaborations uniting diverse expertise to tackle these technologies' complexities. Collaborative efforts among computer science, visual arts, and human-computer interaction are vital for developing innovative solutions that improve user engagement and educational outcomes [27]. Such collaborations facilitate integrating cutting-edge technologies into museum practices, resulting in immersive and interactive experiences that captivate diverse audiences.

Standardization is crucial for effectively deploying AR and interactive technologies across various museum settings. Establishing open standards and frameworks ensures interoperability among different technological platforms, enabling seamless integration of AR applications into existing infrastructures [36]. Standardization streamlines the development process, reducing complexity and costs, allowing museums of all sizes to benefit from these advancements.

Moreover, interdisciplinary collaborations can foster standardized methodologies for evaluating user experience and engagement in AR environments. By establishing consistent metrics and evaluation frameworks, researchers and practitioners can better assess AR applications' effectiveness, leading to informed decisions regarding their design and implementation [31]. This collaborative approach ensures that AR technologies prioritize user-centered design, accessibility, and inclusivity, ultimately enhancing museums' educational and cultural missions.

7.3 User-Centric Design and Accessibility

User-centric design and accessibility are pivotal in developing future technology applications, particularly in augmented reality (AR) and interactive technologies within museums. Emphasizing user-centered design ensures that technological innovations cater to the diverse needs of museum visitors, thereby enhancing engagement and educational outcomes. By focusing on user experience, designers can create intuitive interfaces that facilitate seamless interactions with digital content, enriching the visitor experience [42].

Accessibility is paramount in AR application development, ensuring all visitors, regardless of their abilities, can engage with cultural heritage artifacts. Creating accessible alternatives for common AR tasks is essential for democratizing access to these technologies, enabling users with varying abilities to interact effectively with AR content [56]. This commitment to accessibility highlights AR's transformative potential in providing inclusive educational experiences.

Integrating Artificial Intelligence (AI) into AR systems further enhances user-centric design by offering personalized and context-sensitive interactions tailored to individual visitor preferences and needs [6]. By leveraging AI, AR applications can deliver customized experiences that boost user engagement and satisfaction, allowing visitors to fully explore and appreciate museum exhibits.

Furthermore, user-centered AR design is supported by theories such as the Multiple Resource Theory, emphasizing the necessity for clear notifications that minimize cognitive load and enhance attention [55]. This theoretical framework guides AR interface design, underscoring the importance of intuitive interactions that do not overwhelm users, thereby improving task performance and overall user experience.

7.4 Ethical Considerations and Privacy Concerns

The integration of interactive technologies and augmented reality (AR) in museums necessitates a thorough examination of ethical considerations and privacy concerns to ensure responsible use. A primary ethical challenge involves safeguarding user privacy, particularly concerning camera-based systems used for tangible interaction detection, which may inadvertently capture sensitive data [83]. Addressing these concerns requires robust privacy protections and transparent user consent mechanisms to safeguard personal information and maintain user trust.

Additionally, deploying AR and extended reality (XR) technologies in public spaces raises significant ethical questions regarding user consent and the potential for surveillance [84]. The use of AR head-mounted displays (HMDs) to enhance visual search performance introduces further challenges, as imperfect automation may lead to unintended consequences [61]. These issues highlight the importance of developing unobtrusive methods that encourage positive user behavior while addressing legal and ethical considerations surrounding persuasive technology [85].

The implementation of ARtivism, which involves unsanctioned public art, underscores the need to address privacy and consent issues to ensure ethical compliance [86]. Moreover, integrating AI within AR systems raises ethical implications that necessitate interdisciplinary collaboration to address safety concerns and ensure responsible use of immersive technology [6].

The digitization and preservation of cultural heritage necessitate legal frameworks that respect the cultural and intellectual property rights of communities [17]. Current research faces limitations in data collection methods and participant engagement, underscoring the need for reliable XR hardware and ethical guidelines to maintain research integrity [87].

The increasing integration of interactive technologies and augmented reality (AR) in museum environments raises significant ethical considerations and privacy concerns, necessitating robust frameworks and collaborative initiatives. These frameworks should address complexities related to user participation, data collection, and security measures, as highlighted by recent research into immersive art installations. By fostering collaboration among artists, technologists, and cybersecurity experts, museums can create safer, more engaging experiences that respect user privacy while enhancing cultural engagement [29, 89, 27, 88, 26]. Prioritizing privacy, consent, and ethical use allows museums to harness these technologies to enhance visitor experiences while upholding cultural and social responsibilities.

7.5 Future Research Directions

Future research in interactive technology and augmented reality (AR) in museums presents numerous opportunities for enhancing user engagement and educational outcomes. Expanding audio rendering capabilities to enable continuous playback across multiple 3D models, alongside extensive user studies, can validate these methods' effectiveness [3]. Additionally, refining augmentation techniques by integrating contextual information or experimenting with different generative models could enrich AR experiences [37].

Exploring user awareness and interaction in collaborative AR environments is critical, necessitating the development of mechanisms for content moderation and ownership [8]. Refining existing taxonomies and developing frameworks for implementing VR and AR applications in educational contexts are essential for providing structured guidelines for future technological integration [10].

Moreover, expanding the taxonomy of AR tasks and improving interaction techniques are key areas for exploration. Involving users with disabilities from the design process's outset will ensure that AR applications are inclusive, broadening their applicability across diverse museum settings [56]. Research should also investigate the practical applications of AR in various museum contexts, assess user engagement strategies, and evaluate the long-term impacts of AR on visitor experiences and organizational success.

Further exploration of 3D graph literacy and the effects of different interaction techniques and display configurations on user performance is vital for advancing AR applications in educational settings. Enhancing the integration of Visual Question Answering (VQA) systems and expanding annotated datasets will facilitate meaningful interactions between users and cultural artifacts, allowing for engagement with smart audio guides and AR applications via natural language queries. This development will deepen user understanding and appreciation of artworks, especially as cultural institutions digitize their visual collections. Robust VQA systems, supported by comprehensive annotated datasets, will enable users to explore and discover these collections more effectively, overcoming metadata limitations and enhancing user engagement [22, 35].

An essential research area involves developing immersive and sustained AR experiences that promote deeper engagement with marginalized narratives. This focus leverages AR's potential to disrupt conventional cultural narratives and convey multilayered stories that reveal invisible histories, as demonstrated by projects utilizing location-based AR for social change. By creating interactive experiences that anchor tribal stories to specific sites and address social justice issues, researchers aim to enhance the impact and accessibility of these narratives [78, 29, 82, 30]. Pursuing these research directions will enable the field of interactive technology and AR in museums to evolve, enriching cultural heritage experiences for diverse audiences.

8 Conclusion

The integration of interactive technology and augmented reality (AR) within museum contexts marks a transformative step in cultural heritage presentation and preservation. These technologies have redefined museum experiences by crafting immersive environments that captivate and educate a broad spectrum of audiences. Virtual reality (VR) applications, such as those highlighting the Dunhuang murals, significantly enhance users' comprehension and appreciation of cultural narratives by engaging them with intricate historical stories. The use of actors in VR storytelling further amplifies both educational and entertainment dimensions, resulting in increased user engagement and improved learning outcomes.

The application of medical imaging techniques in projects like IRMA within virtual reality settings exemplifies the transformative potential for archaeological research, offering profound insights into artifacts and their historical contexts. Furthermore, the use of object detection in exploring digital art collections significantly enriches user engagement and discovery, fostering a deeper appreciation for artworks. The Gaussian Heritage Pipeline method emphasizes the role of 3D digitization techniques in improving accessibility to cultural heritage, with substantial implications for museum practices. Customized VR experiences play a crucial role in enhancing museum visits for older adults, underscoring their significance in cultural heritage preservation and facilitating meaningful connections with historical narratives for diverse audiences.

References

[1] Aven Le Zhou, Kang Zhang, and David Yip. Painterly reality: Enhancing audience experience with paintings through interactive art, 2023.

[2] Andres Montero and Borja Belaza. Towards an augmented reality fourth generation social networks, 2017.

[3] Praseedha Krishnan Aniyath, Sreeni Kamalalayam Gopalan, Priyadarshini K, and Subhasis Chaudhuri. Combined hapto-visual and auditory rendering of cultural heritage objects, 2020.

[4] Stefan Krumpen, Reinhard Klein, and Michael Weinmann. Towards tangible cultural heritage experiences – enriching vr-based object inspection with haptic feedback, 2021.

[5] Denise Kahl and Antonio Krüger. Using abstract tangible proxy objects for interaction in optical see-through augmented reality, 2023.

[6] Wangfan Li, Rohit Mallick, Carlos Toxtli-Hernandez, Christopher Flathmann, and Nathan J. McNeese. Leveraging artificial intelligence to promote awareness in augmented reality systems, 2024.

[7] Efstratios Geronikolakis and George Papagiannakis. An xr rapid prototyping framework for interoperability across the reality spectrum, 2021.

[8] Anhong Guo, Ilter Canberk, Hannah Murphy, Andrés Monroy-Hernández, and Rajan Vaish. Blocks: Collaborative and persistent augmented reality experiences, 2019.

[9] Patrick Reipschläger, Tamara Flemisch, and Raimund Dachselt. Personal augmented reality for information visualization on large interactive displays, 2020.

[10] Jiri Motejlek and Esat Alpay. Taxonomy of virtual and augmented reality applications in education, 2021.

[11] Jingling Zhang, Qianjie Wei, Xiaoying Wei, and Mingming Fan. Exploring the design of virtual reality museums to support remote visitation with older adults, 2024.

[12] Annie Yang. Preserving history through augmented reality, 2024.

[13] Rongxuan Mu, Yuhe Nie, Kent Cao, Ruoxin You, Yinzong Wei, and Xin Tong. Pilgrimage to pureland: Art, perception and the wutai mural vr reconstruction, 2023.

[14] Nishant Chaudhary, Mihir Raj, Richik Bhattacharjee, Anmol Srivastava, Rakesh Sah, and Pankaj Badoni. Aipanvr: A virtual reality experience for preserving uttarakhand's traditional art form, 2024.

[15] Selma Rizvic, Dusanka Boskovic, Fabio Bruno, Barbara Davidde Petriaggi, Sanda Sljivo, and Marco Cozza. Actors in vr storytelling, 2020.

[16] M Claudia tom Dieck and Timothy Hyungsoo Jung. Value of augmented reality at cultural heritage sites: A stakeholder approach. *Journal of destination marketing & management*, 6(2):110–117, 2017.

[17] Maciej Grzeszczuk, Kinga Skorupska, Paweł Grabarczyk, Władysław Fuchs, Paul F. Aubin, Mark E. Dietrick, Barbara Karpowicz, Rafał Masłyk, Pavlo Zinevych, Wiktor Stawski, Stanisław Knapiński, and Wiesław Kopeć. Preserving tangible and intangible cultural heritage: the cases of volterra and atari, 2024.

[18] Dheeraj Vagavolu, Akhila Sri Manasa Venigalla, and Sridhar Chimalakonda. Museumviz – towards visualizing online museum collections, 2021.

[19] Laurence Cliffe, James Mansell, Joanne Cormac, Chris Greenhalgh, and Adrian Hazzard. The audible artefact: Promoting cultural exploration and engagement with audio augmented reality, 2024.

[20] David Prochazka and Tomas Koubek. Augmented reality implementation methods in mainstream applications, 2011.

[21] Rob Eagle. Augmented reality as a thirdspace: Simultaneous experience of the physical and virtual, 2023.

[22] Taylor Arnold and Lauren Tilton. Explainable search and discovery of visual cultural heritage collections with multimodal large language models, 2024.

[23] Marilena Alivizatou-Barakou, Alexandros Kitsikidis, Filareti Tsalakanidou, Kosmas Dimitropoulos, Chantas Giannis, Spiros Nikolopoulos, Samer Al Kork, Bruce Denby, Lise Buchman, Martine Adda-Decker, et al. Intangible cultural heritage and new technologies: challenges and opportunities for cultural preservation and development. *Mixed reality and gamification for cultural heritage*, pages 129–158, 2017.

[24] Mara Solen, Nigar Sultana, Laura Lukes, and Tamara Munzner. Delve into earth's past: A visualization-based exhibit deployed across multiple museum contexts, 2024.

[25] Zhenjie Zhao. Engaging audiences in virtual museums by interactively prompting guiding questions, 2019.

[26] Mafkereseb Kassahun Bekele, Roberto Pierdicca, Emanuele Frontoni, Eva Savina Malinverni, and James Gain. A survey of augmented, virtual, and mixed reality for cultural heritage. *Journal on Computing and Cultural Heritage (JOCCH)*, 11(2):1–36, 2018.

[27] Selma Rizvic, Dusanka Boskovic, Vensada Okanovic, Sanda Sljivo, and Merima Zukic. Interactive digital storytelling: bringing cultural heritage in a classroom, 2020.

[28] Behrang Parhizkar, Ashraf Abbas M. Al-Modwahi, Arash Habibi Lashkari, Mohammad Mehdi Bartaripou, and Hossein Reza Babae. A survey on web-based ar applications, 2011.

[29] Rafael M. L. Silva, Erica Principe Cruz, Daniela K. Rosner, Dayton Kelly, Andrés Monroy-Hernández, and Fannie Liu. Understanding ar activism: An interview study with creators of augmented reality experiences for social change, 2022.

[30] Josef Spjut, Fengyuan Zhu, Xiaolei Huang, Yichen Shou, Ben Boudaoud, Omer Shapira, and Morgan McGuire. Experimental augmented reality user experience, 2022.

[31] Stefan Graser, Felix Kirschenlohr, and Stephan Böhm. User experience evaluation of augmented reality: A systematic literature review, 2024.

[32] Marc Satkowski, Wolfgang Büschel, and Raimund Dachselt. Experiences with user studies in augmented reality, 2021.

[33] Wai Tong, Zhutian Chen, Meng Xia, Leo Yu-Ho Lo, Linping Yuan, Benjamin Bach, and Huamin Qu. Exploring interactions with printed data visualizations in augmented reality, 2022.

[34] Hanbing Wang, Junyan Du, Yue Li, Lie Zhang, and Xiang Li. Grand challenges in immersive technologies for cultural heritage, 2025.

[35] Pietro Bongini, Federico Becattini, Andrew D. Bagdanov, and Alberto Del Bimbo. Visual question answering for cultural heritage, 2020.

[36] Julien Antoine Raemy and Robert Sanderson. Analysis of the usability of automatically enriched cultural heritage data, 2023.

[37] Dario Cioni, Lorenzo Berlincioni, Federico Becattini, and Alberto del Bimbo. Diffusion based augmentation for captioning and retrieval in cultural heritage, 2023.

[38] Louie Søs Meyer, Johanne Engel Aaen, Anitamalina Regitse Tranberg, Peter Kun, Matthias Freiberger, Sebastian Risi, and Anders Sundnes Løvlie. Algorithmic ways of seeing: Using object detection to facilitate art exploration, 2024.

[39] Mahtab Dahaghin, Myrna Castillo, Kourosh Riahidehkordi, Matteo Toso, and Alessio Del Bue. Gaussian heritage: 3d digitization of cultural heritage with integrated object segmentation, 2024.

[40] Simin Yang, Ze Gao, Reza Hadi Mogavi, Pan Hui, and Tristan Braud. Tangible web: An interactive immersion virtual realitycreativity system that travels across reality, 2023.

[41] Stéphanie Bertrand, Martha Vassiliadi, Paul Zikas, Efstratios Geronikolakis, and George Papagiannakis. From readership to usership and education, entertainment, consumption to valuation: Embodiment and aesthetic experience in literature-based mr presence, 2019.

[42] Théophane Nicolas, Ronan Gaugne, Bruno Arnaldi, and Valérie Gouranton. From medical imaging to virtual reality for archaeology, 2023.

[43] Ektor Vrettakis, Vassilis Kourtis, Akrivi Katifori, Manos Karvounis, Christos Lougiakis, and Yannis Ioannidis. Narralive – creating and experiencing mobile digital storytelling in cultural heritage, 2019.

[44] Tommy Nilsson, Alan Blackwell, Carl Hogsden, and David Scruton. Ghosts! a location-based bluetooth le mobile game for museum exploration, 2016.

[45] Natasha Moorhouse, M Claudia tom Dieck, and Timothy Jung. An experiential view to children learning in museums with augmented reality. *Museum Management and Curatorship*, 34(4):402–418, 2019.

[46] Chen Zhu-Tian, Yijia Su, Yifang Wang, Qianwen Wang, Huamin Qu, and Yingcai Wu. Marvist: Authoring glyph-based visualization in mobile augmented reality, 2024.

[47] Walter Guyot, Helene Courtois M., and Jacques Toussaint. Digital planetariums as virtual museums for discovering today's science, 2013.

[48] Zhan Wang, Lin-Ping Yuan, Liangwei Wang, Bingchuan Jiang, and Wei Zeng. Virtuwander: Enhancing multi-modal interaction for virtual tour guidance through large language models, 2024.

[49] RamKumar Lakshminarayanan, RD. Balaji, Binod kumar, and Malathi Balaji. Augmented reality in ict for minimum knowledge loss, 2013.

[50] Nikolaos Giakoumidis and Christos-Nikolaos Anagnostopoulos. Autonomous reality modelling for cultural heritage sites employing cooperative quadrupedal robots and unmanned aerial vehicles, 2024.

[51] Joshua Romphf, Elias Neuman-Donihue, Gregory Heyworth, and Yuhao Zhu. Resurrect3d: An open and customizable platform for visualizing and analyzing cultural heritage artifacts, 2021.

[52] Sifan Ye, Ting Wu, Michael Jarvis, and Yuhao Zhu. Digital reconstruction of elmina castle for mobile virtual reality via point-based detail transfer, 2021.

[53] Taha Alfaqheri, Seif Allah El Mesloul Nasri, and Abdul Hamid Sadka. 3d holoscopic imaging for cultural heritage digitalisation, 2018.

[54] Chen Zhu-Tian, Wai Tong, Qianwen Wang, Benjamin Bach, and Huamin Qu. Augmenting static visualizations with paparvis designer, 2024.

[55] Aditya Raikwar, Lucas Plabst, Anil Ufuk Batmaz, Florian Niebling, and Francisco R. Ortega. Ping! your food is ready: Comparing different notification techniques in 3d ar cooking environment, 2024.

[56] Jaylin Herskovitz, Jason Wu, Samuel White, Amy Pavel, Gabriel Reyes, Anhong Guo, and Jeffrey P. Bigham. Making mobile augmented reality applications accessible, 2020.

[57] Mohammed AM AlGerafi, Yueliang Zhou, Mohamed Oubibi, and Tommy Tanu Wijaya. Unlocking the potential: A comprehensive evaluation of augmented reality and virtual reality in education. *Electronics*, 12(18):3953, 2023.

[58] Efstratios Geronikolakis, Paul Zikas, Steve Kateros, Nick Lydatakis, Stelios Georgiou, Mike Kentros, and George Papagiannakis. A true ar authoring tool for interactive virtual museums, 2019.

[59] Lei Chen, Yilin Liu, Yue Li, Lingyun Yu, BoYu Gao, Maurizio Caon, Yong Yue, and Hai-Ning Liang. Effect of visual cues on pointing tasks in co-located augmented reality collaboration, 2021.

[60] Long Chen, Karl Francis, and Wen Tang. Semantic augmented reality environment with material-aware physical interactions, 2018.

[61] Amelia C. Warden, Christopher D. Wickens, Daniel Rehberg, Francisco R. Ortega, and Benjamin A. Clegg. Fast, accurate, but sometimes too-compelling support: The impact of imperfectly automated cues in an augmented reality head-mounted display on visual search performance, 2023.

[62] Chao Shi. Non-user inclusive design for maintaining harmony of real-virtual human interaction in augmented reality, 2019.

[63] Yongquan Hu, Dawen Zhang, Mingyue Yuan, Kaiqi Xian, Don Samitha Elvitigala, June Kim, Gelareh Mohammadi, Zhenchang Xing, Xiwei Xu, and Aaron Quigley. Investigating the design considerations for integrating text-to-image generative ai within augmented reality environments, 2024.

[64] Francesco Vona, Sina Hinzmann, Michael Stern, Tanja Kojić, Navid Ashrafi, David Grieshammer, and Jan-Niklas Voigt-Antons. Investigating the impact of virtual element misalignment in collaborative augmented reality experiences, 2024.

[65] Roberto Balzani, Sebastian Barzaghi, Gabriele Bitelli, Federica Bonifazi, Alice Bordignon, Luca Cipriani, Simona Colitti, Federica Collina, Marilena Daquino, Francesca Fabbri, Bruno Fanini, Filippo Fantini, Daniele Ferdani, Giulia Fiorini, Elena Formia, Anna Forte, Federica Giacomini, Valentina Alena Girelli, Bianca Gualandi, Ivan Heibi, Alessandro Iannucci, Rachele Manganelli Del Fà, Arcangelo Massari, Arianna Moretti, Silvio Peroni, Sofia Pescarin, Giulia Renda, Diego Ronchi, Mattia Sullini, Maria Alessandra Tini, Francesca Tomasi, Laura Travaglini, and Luca Vittuari. Saving temporary exhibitions in virtual environments: the digital renaissance of ulisse aldrovandi – acquisition and digitisation of cultural heritage objects, 2023.

[66] Ichiroh Kanaya, Masataka Imura, and Mayuko Kanazawa. Interactive art to go, 2014.

[67] Elijah Wyckoff, Marlan Ball, and Fernando Moreu. Reducing gaze distraction for real-time vibration monitoring using augmented reality, 2021.

[68] Fang Xu, Tri Nguyen, and Jing Du. Augmented reality for maintenance tasks with chatgpt for automated text-to-action, 2023.

[69] Taylor Arnold, Nathaniel Ayers, Justin Madron, Robert Nelson, and Lauren Tilton. Visualizing a large spatiotemporal collection of historic photography with a generous interface, 2020.

[70] Lorenzo Cocchia, Maurizio Vergari, Tanja Kojic, Francesco Vona, Sebastian Moller, Franca Garzotto, and Jan-Niklas Voigt-Antons. The impact of social environment and interaction focus on user experience and social acceptability of an augmented reality game, 2024.

[71] Antonio Bracco, Federico Grunwald, Agustin Navcevich, Germán Capdehourat, and Federico Larroca. Museum accessibility through wi-fi indoor positioning, 2020.

[72] C. Tollola. Procedural animations in interactive art experiences – a state of the art review, 2021.

[73] Sebastian Barzaghi, Alice Bordignon, Bianca Gualandi, Ivan Heibi, Arcangelo Massari, Arianna Moretti, Silvio Peroni, and Giulia Renda. A proposal for a fair management of 3d data in cultural heritage: The aldrovandi digital twin case, 2024.

[74] Anna V Iatsyshyn, Valeriia O Kovach, Yevhen O Romanenko, Iryna I Deinega, Andrii V Iatsyshyn, Oleksandr O Popov, Yulii G Kutsan, Volodymyr O Artemchuk, O Yu Burov, and Svitlana H Lytvynova. Application of augmented reality technologies for preparation of specialists of new technological era. In *Augmented Reality in Education: Proceedings of the 2nd International Workshop (AREdu 2019), Kryvyi Rih, Ukraine, March 22, 2019*, number 2547, pages 181–200. CEUR Workshop Proceedings, 2020.

[75] Corrie Green. Augmenting heritage: An open-source multiplatform ar application, 2023.

[76] JungHyun Byun, SeungHo Chae, YoonSik Yang, and TackDon Han. Air: Anywhere immersive reality with user-perspective projection, 2018.

[77] Zhiwen Qiu, Armin Mostafavi, and Saleh Kalantari. Use of augmented reality in human wayfinding: A systematic review, 2023.

[78] Tiffany T. Nguyen, Cinthya Jauregui, Sarah H. Sallee, Mohan R. Chandrasekar, Liam A'Hearn, Dominic J. Woetzel, Pinak Paliwal, Madison Nguyen, Isabella 'Amne Gomez, Xinqi Zhang, Lee M. Panich, Danielle M. Heitmuller, Amy Lueck, and Kai Lukoff. Sociotechnical considerations for slam anchors in location-based ar, 2024.

[79] Maud Poulin, Jean-François Boujut, and Cédric Masclet. Analysis of the co-design activity: influence of a mixed artifact and contribution of the gestural function in a spatial augmented reality environment, 2019.

[80] Xinyi Liu, Xuanru Meng, Becky Spittle, Wenge Xu, BoYu Gao, and Hai-Ning Liang. Exploring text selection in augmented reality systems, 2022.

[81] Shahin Doroudian. Collaboration in immersive environments: Challenges and solutions, 2025.

[82] Hope Schroeder, Rob Tokanel, Kyle Qian, and Khoi Le. Location-based ar for social justice: Case studies, lessons, and open challenges, 2023.

[83] Thomas Kosch and Albrecht Schmidt. Enabling tangible interaction through detection and augmentation of everyday objects, 2020.

[84] Verena Biener, Eyal Ofek, Michel Pahud, Per Ola Kristensson, and Jens Grubert. Extended reality for knowledge work in everyday environments, 2021.

[85] Fachrina Dewi Puspitasari and Lik-Hang Lee. Review of persuasive user interface as strategy for technology addiction in virtual environments, 2022.

[86] Lucy Jiang. Artivism: Ar-enabled accessible public art and advocacy, 2024.

[87] Jack Ratcliffe, Francesco Soave, Nick Bryan-Kinns, Laurissa Tokarchuk, and Ildar Farkhatdinov. Extended reality (xr) remote research: a survey of drawbacks and opportunities, 2021.

[88] Kathryn Lichlyter, Urvashi Kishnani, Kate Hollenbach, and Sanchari Das. Understanding professional needs to create privacy-preserving and secure emergent digital artworks, 2024.

[89] Jean-Daniel Taupiac, Nancy Rodriguez, and Olivier Strauss. Immercity: a curation content application in virtual and augmented reality, 2018.

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