A Systematic Review of Integrating Mixed Reality and Artificial Intelligence in Museums: Enhancing Visitor Experiences and Innovating Exhibit Design

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Abstract

With the development of immersive technologies and artificial intelligence (AI), museums are increasingly adopting mixed reality (MR) and AI to transform visitor experience and perceptions. However, there is limited literature on the combined application of AI and MR (AIMR) in museums and the potential for integrating these technologies. This paper systematically reviews the implications of MR and AI in museums, identifying key topics as well as design guidelines. Preliminary results indicate that immersive and customized experiences are major themes in AIMR applications in museums. Emerging MR themes include social interaction and enhanced artifact displays, while AI developments focus mainly on intelligent virtual assistants and artifact detection.

Keywords: Mixed Reality, Artificial Intelligence, Museum, Systematic Review, HCI, UX.

1. Introduction

Museums represent informal educational spaces, offering diverse navigation methods and providing visitors with opportunities to learn about culture and art (Chen & Lai, 2020). Incorporating extended reality (XR) technologies, including virtual reality (VR), augmented reality (AR), and mixed reality (MR), in museums enhances the learning experience by introducing innovative immersive approaches. MR blends real and virtual worlds, AR overlays digital information on reality, VR creates immersive simulated environments, and AI refers to machine intelligence processes. In museums, these technologies enhance exhibits and personalize visitor experiences (Speicher et al., 2019; Hammady et al., 2020). These technologies enrich the tour experience beyond traditional frameworks and potentially enhance future visitation intentions and behaviors (Chen & Lai, 2020; Hammady et al., 2021). Cultural heritage institutions, including museums, are deploying XR technologies for various purposes such as enhancing exhibitions, aiding reconstruction efforts, educational purposes, and establishing virtual museums (Bekele et al., 2018). MR, positioned within the reality-virtuality continuum by Milgram et al. (1995), enables users to interact with virtual elements, providing deeper immersion and fostering novel interactions (Ke et al., 2019). Many museums have introduced MR technologies to bring originally static cultural relics to life or to serve as tour guides, providing information about artifacts through multi-sensory channels (Chin et al., 2023; Hammady, 2021; Martí-Testón et al., 2021). For instance, the ancient Kennin-ji Temple in Kyoto applied MR technique to the "MR Museum in Kyoto" in 2018, offering an immersive tour led by a virtual monk and enriching the experience of viewing historical artworks with the use of Microsoft HoloLens MR glasses. Therefore, the use of MR technologies in museums not only advances the presentation of cultural artifacts but also significantly enhances visitor engagement and educational outcomes. MR applications can provide both utilitarian and hedonic value to visitors, influencing their behavior (Babin & Attaway, 2000; Bridges & Florsheim, 2008), as perceived by users. Utilitarian value refers to practical benefits like convenience and functionality, affecting user intention (Strahilevitz &

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Myers, 1998; Rohm & Swaminathan, 2004). Hedonic value, as defined by Chaudhuri & Holbrook (2001), involves emotional or sensory enjoyment, influencing emotional connection and satisfaction. These two values are pivotal in consumer behavior (Hanzaee & Rezaeyeh, 2013).

Unlike VR, which surrounds users with a completely fictional environment, MR technology enables immersive exploration and learning during museum visits. It seamlessly blends digital content with real-world environments, enhances exhibitions, and transforms static displays into interactive narratives. In other words, the use of MR aims to complement the artifacts instead of replacing them (Speicher et al., 2019; Kim & Choi, 2021; Chin et al. 2023). Given their significance for enhancing visitor experiences and museum profitability, this study explores the potential for integrating MR and AI technologies in museums. While MR applications have been widely adopted, the integration of AI offers additional potential to personalize and enrich visitor interactions. Understanding how these technologies can work together is crucial, as AIMR has the potential to not only enhance visitor engagement but also innovate museum operations (Hammady et al., 2021). This review highlights these synergies by examining recent developments in both MR and AI applications within the museum context.

The rise of deep neural networks, particularly large language models (LLMs), fueled a boom in generative AI systems in the early 2020s. Applications like ChatGPT, Copilot, or Midjourney have significantly advanced, demonstrating remarkable capabilities in both text and image generation. For example, Trichopoulos et al. (2023) developed a museum guide using ChatGPT-4 to assist visitors in navigating extensive collections and understanding the value of artifacts. By leveraging the model's natural language capabilities, the guide offers personalized, engaging, and informative experiences. Cetinic and She (2022) highlight current creative applications of AI in visual arts, employing deep learning and computer vision techniques to analyze existing artworks, thereby potentially augmenting utilitarian value for museum visitors and staff. Artifact detection systems in museums represent one of the AI-related features that strengthen utilitarian value, as demonstrated by the "Exhibition of Fake Art" by Ferrato et al. (2022) at Roma Tre University. This system utilized R-CNN to achieve high accuracy in detecting specific objects in images.

The implementation of wearable MR has facilitated seamless navigation for museum visitors, while AI deployment has enhanced the intelligence of museum services. The use of MR and AI technologies in a museum has shown their potential to advance visitor experience as well as enhance the consequent learning performance. However, limited research is devoted to evaluating the synergy of utilizing AI and MR (AIMR) in museums. This review aims to address this gap by identifying key themes in AIMR applications and offering design guidelines for these systems in museum contexts. Our study contributes to understanding how AI and MR can transform museum practices and visitor experiences, providing a comprehensive overview of this emerging integration. This study, therefore, reviews the implications and influences of AIMR technologies on museum practices and visitor experiences to provide a comprehensive knowledge of the current development of these technologies and demonstrate their importance for museums. This review focuses exclusively on studies published between 2020 and 2024 to highlight the latest advancements in MR and AI technologies within museum settings. This timeframe was chosen to ensure the review reflects the most current trends and innovations in these rapidly evolving fields. However, we acknowledge that limiting the scope to this period may exclude valuable insights from earlier museum MR research. Despite this limitation, the selected timeframe enables a state-of-the-art analysis and review of the developments in MR and AI, particularly in light of the significant technological progress in recent years.

The rest of the paper is organized as follows: Section 2 discusses the approach used for the systematic literature review process and the research agenda development and assessment. Section 3 describes the results of our analysis of the collected studies and describes how the utilization of MR and AI technologies can augment visitors' experiences within the museum context. Section 4 concludes the implications and suggests future directions.

2. Research methodology

This study employs a systematic literature review to gather pertinent research. Articles were selected following the specific steps and criteria outlined by the PRISMA (preferred reporting items for systematic reviews and meta-analyses) guidelines. Figure 1 illustrates the complete literature collection and assessment processes based on the PRISMA framework. The main steps include study identification, screening, and eligibility assessment. The details are introduced in the sections below:

2.1. Data collection

Initially, we collected literature on the applications of MR in museums and AI in museums from three databases, Scopus, ProQuest, and Google Scholar, using the following search terms in the title:

(a) MR in museums query: ("MR" OR "Mixed Reality") AND ("museum" OR "gallery")

(b) AI in museums query: ("Artificial intelligence" OR "AI" OR "generative artificial intelligence" OR "intelligent systems" OR "machine learning" OR "deep learning" OR "natural language processing" OR "NLP") AND ("museum" OR "gallery")

We then restricted the search results to relevant journals or conference papers written in English and published between 2020 and mid-April 2024, focusing on recent AI advancements (such as generative AI like ChatGPT) that may impact AI applications in museums. After removing duplicates, we collected a total of 92 academic articles.

2.2. Study selection and assessment

To evaluate the relevance and quality of the selected research literature, this study further screens the literature through the following steps:

(1) Source Verification: We verified whether the publication sources, including journals or conferences, are listed in Google Scholar's Top Publications (https://scholar.google.com/citations?view_op=top_venues). Literature that could not be located was subsequently excluded (n=24). Additionally, we excluded studies with unavailable full text (n=15).

(2) Content Examination: We excluded studies where the full text or abstracts did not contain empirical studies or lacked user participation in experiments (n=8). For MR-related literature, we excluded those that did not use MR-based Head-Mounted Device (HMD) as the main device (n=6).

(3) Topic Relevance: We reviewed the abstracts or full texts to exclude literature that was not directly related to the themes regarding MR or AI in the museum contexts (n=19). For instance, the use of AI/MR should play a primary role in the research questions or objectives, and the impact of AIMR applications within museums should be the central topic of discussion. After the screening and eligibility stages, a total of 20 studies were included in the review, with 7 related to MR applications and 13 related to AI techniques. Among these studies, 7 are conference papers, and 13 are journal articles. These studies not only examine the integration of immersive technologies in AI but also reflect the recent trend toward the convergence of emerging technologies.

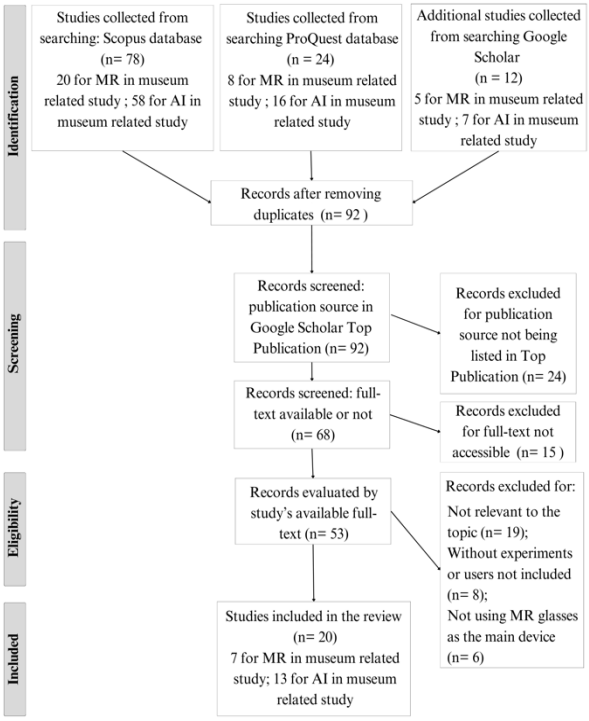

Figure 1. PRISMA flow diagram for the process of study collection, screening, and evaluation.

3. Result and discussion

This study categorizes the key features of MR and AI applications into hedonic and utilitarian values. The theoretical basis is initially rooted in marketing and e-commerce research (Chiu et al., 2014). Hedonic value refers to the emotional and sensory pleasure derived from an experience. In contrast, utilitarian value pertains to the practical and functional benefits that serve specific goals, such as convenience or efficiency. As the hedonic and utilitarian concepts have been widely used in the investigation of consumer behavior, the present study, therefore, adopts these concepts to examine AI and MR applications in museums. In our AIMR context, hedonic value focuses on the enjoyment and immersive engagement that these technologies offer to users, while utilitarian value relates to the enhancement of practical service functions, such as improving accessibility or providing personalized information. Drawing on these well-established concepts allows us to develop a robust framework for analyzing how AIMR technologies influence both the

emotional and functional aspects of visitor experiences. The results are included in Tables 1-4. Section 3.1 examines the latest MR applications in museums. Section 3.2 highlights the innovative use of AI systems in museum contexts.

3.1. Mixed Reality applications in museums

Among the literature collected in this study, seven articles specifically focus on the MR applications in museums. The main features can be categorized into social interaction, enhanced display of artifacts, immersive or customized experience, and multimedia material display of artifacts. The first two features are related to hedonic value, while the latter two are associated with utilitarian value. Tables 1 and 2 provide an overview of the functions of MR applied in museums from 2020 to 2024, concentrating on aspects of hedonic and utilitarian value, respectively.

3.1.1. Enhance the hedonic value of Museum Exhibits

This study reveals an increasing trend of MR applications in museums, particularly in social interaction and enhanced display of artifacts. Key features include shared experiences between co-visitors, interactive gamification, interaction with virtual guide tours, reconstruction of artifacts, and real-time art suggestions.

3.1.1.1. Social interaction. MR applications encourage social interaction by not only promoting interactive entertainment between individuals and exhibits, but also encourages shared experiences for multiple users. Hammady et al. (2021) developed "MuseumEye," which includes the "Knowledge Scale Game" to motivate visitors to uncover hidden clues in virtual antiques, encouraging further explanations and enhancing information retention. This gamification feature allows all interactions to be accessible to co-visitors. Visitors can capture and share photos, fulfilling the inclination to take photographs and fostering discussions. Another common MR function is virtual guided tours. For instance, "AlmoinaAR" by Martí-Testón et al. (2021) features a virtual guide for immersive storytelling and presentation. Similarly, "MuseumEye" includes a historical virtual avatar from Ancient Egypt guiding visitors and presenting narration along with visual materials such as videos, images, and 3D artifacts (Hammady et al., 2021). These virtual guides enhance tourist engagement by facilitating interaction with holographic content.

Table 1. Overview of key functions related to the *hedonic* value of MR applied in museums.

Features	Key Functions	Reference
Social Interaction	Shared Experience between Co-visitors	Hammady et al. (2021)
	Interactive Gamification	Hammady et al. (2021)
	Interact with Virtual Guide Tours	Hammady et al. (2021) Martí-Testón et al. (2021)
Enhanced Display of Artifacts	Reconstruction of Artifacts	Martí-Testón et al. (2021) Trunfio et al. (2022)
	Real-Time Art Suggestions	Huang et al. (2020)
	Innovative Storytelling in Historical Contexts	Hammady et al. (2020) Trunfio et al. (2022)

3.1.1.2 Enhanced display of artifacts. Trunfio et al. (2022) conducted a survey in a museum that integrated MR with physical exhibits and immersive historical content. The study found that MR improved visitor experience by providing new interactions and virtual spaces, and also encouraged behaviors such as revisiting and recommending the museum. Regarding content presentation, user accessibility is crucial for designing user interactions, such as system layout, gesture control, and avatar animation. Hammady et al. (2020) structured their system into three interactive layers to manage content and interaction: an interface control layer for scene behaviors (e.g., start/pause), an avatar layer for the virtual narrator, and a scene layer for surrounding scenes and animated models. This layering avoids chaos and ensures well-structured content delivery. An advanced MR museum application may include a content suggestion system. Integrating such a system into their virtual gallery project allows users to browse design suggestions in real-time by comparing the color and style compatibility of different art items (Huang et al., 2020).

3.1.2. Enhance the utilitarian value of museum exhibits

Our study found various functionalities that enhance the utilitarian value for user experience in museums, which can mainly be divided into two aspects: immersive or customized experience and multimedia material display of artifacts. Table 2 provides examples of MR applications with this focus.

3.1.2.1. Immersive or interactive experience. Huang et al. (2020) introduced an interactive MR design tool for creating and visualizing gallery walls. User studies showed that the MR interface significantly reduced manual adjustments or manual searching through a large database of items without compromising design quality. This tool enhanced user engagement through intuitive and immersive visualization, demonstrating the potential of MR technology in customizing museum exhibits and increasing the time users spend in the museum by suggesting artifacts of interest. Furthermore, adding user location awareness can enhance experiences even more. Aoki et al. (2023) developed an MR-guided museum tour system using HoloLens 2 and Immersal's Visual Positioning System (VPS) for self-positioning, managing audio, 2D images, and 3D models based on user location. Results showed that 84% of participants gave positive feedback, with more than half willing to pay double the ticket price for such experiences. Managing visitor flow is also crucial. Hammady et al. (2021) demonstrated that focusing sensor registration on specific artifacts directs visitors to the next relevant item, preventing overcrowding. Similarly, Martí-Testón et al. (2021) designed interactive labels activated by position and gaze, enriching visitor engagement through reconstructions and stories of buildings. Educational applications of MR also show significant promise. Chin et al. (2023) used MR-based learning content to provide contextually relevant multimedia materials based on student location, enhancing the learning experience. Their research on physical interaction with artifacts using gestures and voice commands allowed students to engage with 3D virtual models, further enhancing their understanding and engagement.

3.1.2.2 Multimedia Material Display of Artifacts. In the realm of multimedia material display, Muñoz et al. (2020) developed a novel human-machine interface for the Almoina Archaeological Museum in Valencia. They integrated 3D assets, animations, and pre-recorded tour videos, creating an immersive experience that brings historic scenes to life. Virtual tokens, such as ancient coins, triggered pre-recorded videos, stimulating exploration and engagement. Audio content also plays a significant role in enhancing the museum experience. Both Muñoz et al. (2021) and Hammady et al. (2021) incorporated audio narrations, allowing users to focus on viewing artifacts while absorbing narrated information. This approach enhances the storytelling experience, making museum visits more informative.

Table 2. Overview of key functions related to the *utilitarian* value of MR applied in museums.

Features	Key Functions	Reference
Immersive or Interactive Experience	Customization of MR content	Huang et al. (2020)
	User Location Awareness	Aoki et al. (2023) Chin et al. (2023) Hammady et al. (2021) Martí-Testón et al. (2021)
	Physical Interaction with Content of Artifacts	Chin et al. (2023) Hammady et al. (2021)
Multimedia Material Display of Artifacts	Multimedia Material Display of Artifacts	Chin et al. (2023) Hammady et al. (2021) Martí-Testón et al. (2021) Trunfio et al. (2022)
	Feature Extraction and Image Recognition	Chin et al. (2023)

3.2. Artificial Intelligence applications in museums

Among the literature collected in this study, 13 articles are related to the innovative adoption of AI in museums. AI has become an essential tool in enhancing the interestingness and engagement of museum exhibits. By leveraging AI technologies, museums can create interactive, personalized, and immersive experiences that captivate visitors and enrich their understanding of cultural heritage. Tables 3 and 4 provide an overview of the key functions of AI applied in museums from 2020 to 2024. These themes will be detailed in sections 3.2.1 and 3.2.2.

3.2.1. Enhance the hedonic value of museum exhibits

A growing number of innovative AI applications are focused on enhancing museums' immersive and tailored experiences, as well as providing intelligent virtual assistants. These functionalities such as chatbot design and tailor digital VR museums can simultaneously improve the overall hedonic value of museum visits.

3.2.1.1. Immersive and tailored experience. Winter et al. (2022) highlight the potential of low-power machine learning (ML) technologies in engaging museum visitors. The study utilizes an interactive application that uses human pose estimation and gesture classification to allow visitors to interact with projections of historical interior designs. This application runs on consumer-level hardware, ensuring privacy by processing data locally and eliminating the need for high-power computational resources. Their empirical evaluation reveals that despite occasional tracking inaccuracies, the ML-driven interaction significantly enhances visitor engagement and motivates them to learn more about the exhibited designs. Winter et al.'s (2022) study shows the capability of low-power ML to create highly engaging and educational museum experiences. Continuing the exploration of AI applications, Luo et al. (2024) explore the use of AI in designing VR environments for digital museums. By integrating AI-driven image processing and Spiking Neural Networks (SNN) for image segmentation, their study enhances the clarity and responsiveness of VR experiences, thereby reducing user discomfort such as vertigo. Luo et al. (2024) affirm that AI can significantly improve the comfort and interactivity of digital museum environments, making exhibits more engaging and accessible. They also demonstrate VR environments can be tailored to user preferences and enhanced for interaction and emotional engagement. The findings support the role of AI in creating immersive and emotionally satisfying museum experiences that captivate and educate visitors. Additionally, this research emphasizes the practical implications of using AI to overcome technical limitations and enhance the overall user experience in VR applications.

Table 3. Overview of key functions related to the *hedonic* value of AI applied in museums.

Features	Key Functions	Reference
Immersive and Tailored Experience	Interact with objects by application	Mudassar et al. (2021)
	Tailor digital VR museum	Luo et al. (2024)
	Interactive Design	Winter et al. (2022)
Intelligent Virtual Assistant	Chatbot	Ceuca et al. (2021) Gollapalli et al. (2023) Liang et al. (2024)
	Avatar Building	Chang et al. (2021)

3.2.1.2. Intelligent virtual assistant. The study by Gollapalli, Du, and Ng (2023) introduces ArtMuse, an AI-powered chatbot designed to engage gallery visitors through reflective questioning. Unlike traditional question-answering systems that focus on factual queries, ArtMuse generates open-ended, reflective questions aimed at stimulating informal learning and deeper engagement with artworks. The system employs a combination of extractive question answering and open-domain chitchat models to generate fluent and context-specific questions about paintings. User evaluation studies indicate that ArtMuse effectively enhances visitor engagement by prompting them to think critically about the visual and emotional aspects of the artworks. Building on the

theme of enhancing visitor engagement, Ceuca, Rednic, and Chifu (2021) address the challenge of maintaining visitor interaction and safety during the COVID-19 pandemic through the development of an NLP-based chatbot for the Art Museum in Baia-Mare. The chatbot is designed to replace human guides, answering visitors' questions about exhibits, artists, and art movements using a robust natural language processing model. The system supports both text-to-speech and speech-to-text communications, ensuring a seamless and interactive visitor experience. This chatbot not only facilitates safe, contactless interaction but also enriches the museum visit by providing detailed and accurate information about the exhibits. Similarly focusing on innovative visitor experiences, Liu, Huang, Lin, and Sun (2021) present "Digital Fabrication," an innovative digital artwork that uses ML to create an immersive virtual museum experience. Visitors interact with digital avatars in a 3D-based virtual space, guided by non-player characters (NPCs). The system employs pose recognition technology to personalize the avatars based on visitors' physical movements, fostering a unique connection between the real and virtual worlds. This interactive approach not only attracts visitor attention but also encourages them to explore and reflect on their virtual identities. Extending the application of AI in educational contexts, Liang, Hwang, Hsu, and Yeh (2024) explore the use of AI-based chatbots within alternate reality games (ARGs) to enhance educational experiences in museums. Their study developed a smart learning partner named Bubi, integrated into an ARG system designed to support students' active learning. The chatbot provides adaptive feedback and personalized support, addressing individual learners' needs and improving their metacognitive skills. The results show significant improvements in students' engagement and learning outcomes, demonstrating the effectiveness of AI in facilitating interactive and self-regulated learning in museum contexts.

3.2.2. Enhance the utilitarian value of museum exhibits

Our review identifies two main trends regarding the use of AI applications to increase the utilitarian value of museum exhibits: Artifact Detection and Personalized Experience. The goal is not only to change users' traditional perceptions of museums but also to enhance the efficiency of museum professionals. Key functions include user behavior analysis, pose estimation and gesture recognition, and museum artifact recognition or classification.

3.2.2.1. Personalized experience. Paolanti et al. (2022) developed "Senseable Self-Adapting Museum Environment" (SeSAME) to collect and analyze visitor behavior throughout tours. Using RGB-D cameras and re-identification techniques, SeSAME employed a multimodal deep neural network to analyze movements and interactions. Their study showed that 2D-CNNs performed better with RGB features alone, while 3D-CNNs excelled with both RGB and depth features, achieving higher accuracy in person re-identification. Winter et al. (2022) created a prototype using a pre-trained classifier based on body pose data and a k-nearest neighbors (k-NN) algorithm to classify human gestures. This system enhanced engagement by turning users' hands into virtual paint brushes to reveal designs on a screen during tours. Enhancing learning performance is another significant application of AI. Puspasari et al. (2023) proposed a system that generates quizzes matching user profiles to boost learning engagement. Their research introduced new indicators—museum visitor numbers and the percentage increase in cognitive abilities—to measure the educational performance of museums. Sensitivity analysis showed that museums offering both physical and virtual experiences had the best educational performance. A follow-up study by Ermatita et al. (2023) presents a virtual museum model that incorporates ML techniques to enhance cognitive performance in cultural education. This virtual museum features AR/VR, interactive quizzes, and multimedia content, providing a dynamic learning environment. The ML algorithms predict student interests and tailor the content accordingly, significantly improving cognitive performance, as evidenced by improved post-test scores. This study demonstrates the effectiveness of ML in creating virtual museums that are not only engaging but also educational, transforming the traditional museum experience into an interactive learning journey. In addition, this study highlights the adaptability of virtual museums in response to challenges such as the COVID-19 pandemic, ensuring continuous educational engagement.

3.2.2.2. Artifacts detection. AI also significantly enhances artifact detection in museums, improving usability and visitor experience. Ferrato et al. (2022) demonstrated this by using low-cost equipment, such as simple badges and off-the-shelf RGB cameras, in conjunction with Faster R-CNN, a state-of-the-art deep neural network. This system successfully detected specific objects in images and video sequences with high accuracy, as evidenced by its performance at the "Exhibition of Fake Art" at Roma Tre University. By analyzing visitor behavior in real-

time, the system provided personalized experiences and improved museum management. Additionally, Luo et al. (2024) explored the use of AI to enhance image clarity and reduce vertigo in VR environments by optimizing image acquisition and segmentation with SNN. Their study, based on the simulator sickness questionnaire (SSQ) scale, reported increased comfort and satisfaction among users, highlighting the positive impact of AI on cultural communication.

Table 4. Overview of key functions related to the *utilitarian* value of AI applied in museums.

Features	Key Functions	Reference
Personalized Experience	Profile Personalized and Recommendation	Ivanov (2023) Puspasari (2022; 2023)
	Users' pose Estimation and Gesture	Winter et al. (2022)
	User Behavior Analysis	Ferrato et al. (2022) Paolanti et al. (2022)
	Enhance Learning	Puspasari (2023) Ermatita et al. (2023)
Artifacts Detection	Museum Artifacts Recognition or Classification	Ferrato et al. (2022)
	Image Enhancement using SNN	Luo et al. (2024)
	Detect Museum Artifacts using CNN	Mudassar et al. (2021)

4. Discussion and conclusion

Through an extensive literature review and analysis, we have categorized the retrieved papers into two major categories: MR-based applications and AI-oriented applications. This categorization allows for a comprehensive understanding of the distinct yet complementary roles that MR and AI technologies play in modernizing and optimizing museum experiences.

MR-based applications focus on social interaction, enhanced artifact display, and immersive experiences. These applications aim to create engaging experiences and interactive environments, allowing users to connect with exhibits and each other more deeply. Enhanced artifact displays utilize MR technology to provide detailed and dynamic views of objects, enriching the educational experience and technology in museums, the resulting immersive experiences leverage virtual and augmented reality to transport users to different times and places, making museum visits more educational and impactful.

AI-oriented applications focus on personalizing user experiences, implementing intelligent virtual assistants, and utilizing ML techniques for artifact detection. These applications aim to tailor museum visits to satisfy individual preferences as well as enhance user engagement in the exhibits. Through user profiling, intelligent virtual assistants can provide personalized tours, answer visitor questions in real time, and offer recommendations based on user interests. Additionally, ML techniques are employed to accurately detect, classify, and provide information about artifacts, making the exhibits more interactive and informative. By integrating these AI technologies, museums can offer a more customized and enriching experience, advancing how visitors interact with museum exhibits and optimizing their learning experience.

Our review demonstrates the benefits of integrating MR and AI, which can significantly improve the museum experience by enhancing user interactions and offering personalized content. For example, combining MR's immersive environments with AI's ability to tailor content based on visitor behavior can create more engaging and satisfying experiences. These technologies not only boost visitor engagement but also contribute to the operational efficiency of museums. However, much of the current research focuses on AI integration with AR or VR, which may lead to suboptimal visitor experiences. A more targeted integration of AI with MR could offer a seamless and more effective approach to enhancing museum exhibits. Among the 13 AI-related studies collected for this research, five works explore AI combined with AR/VR applications to enhance user-centered presentations when physical access is limited. Khan et al. (2021) developed a museum AR application that utilizes a CNN deep learning model to

recognize artifacts and display multimedia information. Additionally, by integrating VR and AI techniques, the SMBII museum developed a virtual tour app that provides a 360-degree immersive view with exhibition recommendations (Puspasari, 2022, 2023). The use of AI models in AR/VR applications in museums demonstrates significant potential to integrate AI into MR, providing seamless immersive interactions with physical exhibits and virtual guides of historical content. Hammady et al. (2021) proposed using AI to emulate the role of a human museum guide or mentor within their MR system, "MuseumEye." However, due to the limitations of AI at the time the system was developed, the AIMR system supported only one-way communication and was unable to deviate from predefined content, as outlined in their exploratory study. As AI has advanced in recent years, we believe AIMR will provide multilingual support, multimodal interactions, and more natural conversational contexts tailored to users' needs. By leveraging the strengths of MR and AI, museums can craft more engaging, educational, and personalized experiences for visitors.

From a design guideline viewpoint, future work should place greater emphasis on integrating MR and AI. Additionally, with regard to enhancing the hedonic value of museum exhibits, our findings showed that the concept of NPCs was rarely discussed in previous review papers. Incorporating AI-based avatars and interactive NPCs into MR environments presents a significant opportunity to strengthen visitor engagement through diverse and immersive interactions. Building on this potential, our future work actively explores and develops an AIMR system that integrates AI-guided NPCs to further enhance museum experiences. Combining AI-based avatars with interactive, AI-driven NPCs that stay around specific exhibits within MR HMD could enhance the museum experience by providing more diverse interactive elements, thereby increasing user engagement and participation. Regarding utilitarian value, it would be beneficial to integrate AI functionalities, particularly chatbot features highlighted in previous AI-related literature (Ceuca et al., 2021; Gollapalli et al., 2023; Liang et al., 2024), into MR applications. This could broaden the system's accessibility to a wider range of users, including those with hearing impairments or those accustomed to asking for answers, aiming to provide users with a more comprehensive exhibition experience.

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