

# A Conceptual Model for Integrating Mixed Reality and Artificial Intelligence in Cultural Heritage Application

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## ABSTRACT

*This study conducts a systematic literature review (SLR) to establish a conceptual framework of Mixed Reality (MR) and Artificial Intelligence (AI) in cultural heritage applications, aiming to enhance user engagement through a conceptual model. The review identifies four key dimensions namely, immersion, adaptivity/ personalization, embodiment, and interactivity, as critical factors influencing presence and engagement. Through the synthesis of 21 studies, the proposed conceptual model demonstrates how embodiment, immersion, interactivity, adaptive and personalization collectively strengthen user presence and engagement. Immersion establishes the psychological foundation for presence, reinforced by dynamic AI-driven content and contextualized experiences. Adaptivity and personalization enable systems to respond to user preferences, fostering repeated interaction and experience sharing. Embodiment, through body ownership and perspective-taking, transforms users into active narrative agents, deepening emotional and cognitive involvement. Interactivity, supported by multimodal inputs and gesture-based controls, acts as a direct driver of engagement by enabling responsive and participatory storytelling. Collectively, this conceptual model provides evidence that AI-MR integration strengthens the presence and engagement relationship for cultural heritage preservation, interpretation, and public participation.*

**Keywords:** mixed reality, artificial intelligence, cultural heritage application.

## 1. Introduction

Cultural heritage plays a vital role in preserving collective identity, transmitting cultural values, and fostering public understanding of the past. However, the presentation of cultural heritage are still largely dominated by conventional media, such as textual explanations, static images, or non-interactive displays, which often position audiences as passive recipients of information. These representational approaches tend to limit user's experiential involvement, as they provide minimal opportunities for interaction, contextual exploration, or personal engagement with heritage content.

Recent advances in immersive technologies, particularly Mixed Reality (MR), offer new opportunities for presenting history as an experiential and emotionally engaging. MR is a technology that combines physical world and virtual world to create a new environment where physical digital objects coexist and interact in real-time (Aloqaily et al., 2023). By integrating physical environments with digital heritage content, MR allows users to perceive themselves as situated within culturally significant spaces rather than merely observing them from an external perspective. This enhanced sense of presence supports deeper immersion, enabling users to engage more meaningfully with heritage narratives and spatial contexts. As a result, users are not only exposed to heritage information but are also able to experience cultural heritage as an embodied and context-rich encounter, thereby strengthening emotional involvement and enriching overall experiential quality.

MR is characterized by three main elements: immersion, information, and interactivity (Lee, 2025; Rokhsaritalemi et al., 2020). Immersion refers to the extent to which technology can provide users with the experience of seemingly undergoing the displayed events (Gruber & Kaplan-Rakowski, 2024). Immersive technology can also foster strong emotional engagement, allowing visitors to experience the past more personally and deeply (Kazlauskaitė, 2022; Dima et al., 2024; Škola et al., 2020; Dubovi, 2022; Hammady et al., 2020). Information is a virtual object that being placed in time and space in the user environment (Rokhsaritalemi et al., 2020).

Interactivity relates to the extent to which users can interact with and control their experience, for example through controllers (Makransky & Petersen, 2021).

In parallel, Artificial Intelligence (AI) introduces adaptive and interactive dimensions to the presentation and interpretation of cultural heritage. AI enables dialogic and responsive interactions that allow users to engage with heritage narratives in a more personalized and participatory manner, such as exploring multiple perspectives, responding to contextual prompts, or interacting with virtual agents representing cultural or historical figures. When integrated with Mixed Reality (MR), AI has the potential to transform cultural heritage experiences from predominantly one-directional representations into dynamic and interactive environments. This integration supports higher levels of user engagement by fostering sustained attention, a stronger sense of agency, and deeper involvement with heritage content, thereby contributing to a more meaningful and coherent user experience.

In immersive cultural heritage applications, user experience is strongly influenced by how effectively user engagement is embedded within the system design. From a Human Factors and Ergonomics (HFE) perspective, the effectiveness of an immersive experience can be evaluated based on the extent to which the design maintains sustained engagement through an appropriate balance between cognitive load, interaction mechanisms, and content presentation (International Organization for Standardization, 2010). Poor alignment among these factors may lead to cognitive overload or disengagement, thereby diminishing the experiential value of the system (O'Brien et al., 2022).

Despite the growing interest in immersive and intelligent technologies for cultural heritage applications, existing studies predominantly emphasize technical implementation, system performance, or comparative evaluations of media platforms (Yu et al., 2025). Based on our preliminary study, there remains a notable lack of conceptual research that systematically explains how MR and AI can be integrated to enhance user engagement and overall quality of experience in cultural heritage contexts. This conceptual gap limits a deeper theoretical understanding of how immersive and interactive technologies can be designed to support meaningful engagement, and experiential resonance in the interpretation of cultural heritage.

Therefore, this article presents a systematic literature review that establishes a conceptual framework for integrating Mixed Reality and Artificial Intelligence within cultural heritage experiences, specifically focusing on driving user engagement and fostering meaningful user experiences. By articulating the relationships between adaptive & personalization, immersion, interaction, embodiment and engagement, this study seeks to contribute a theoretical foundation to guide future research and design practices in MR-AI based cultural heritage applications.

## 2. Method

A systematic literature review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines. The Scopus database was selected as the primary source for literature retrieval due to its comprehensive coverage of high-quality, peer-reviewed publications and its strong interdisciplinary scope encompassing immersive technologies, artificial intelligence, cultural heritage, user engagement and user experience research. The search strategy was designed to capture studies situated at the integration of Mixed Reality (MR), Artificial Intelligence (AI), and historical or cultural heritage contexts. To achieve this, the query integrated technological, experiential, and heritage-related dimensions, enabling the identification of research that addresses both system design and user-centered aspects in historical reconstruction and heritage interpretation. The complete search string used in this study is presented in Table 1.

**Table 1.** Search string

Keyword	Search string
Mixed Reality	"Mixed Reality"
Artificial Intelligence	"artificial intelligence" OR "AI" OR "intelligent agent" OR "generative artificial" OR "generative artificial intelligence" OR "intelligent systems" OR "machine learning" OR "deep learning" OR "natural language processing" OR "NLP"
Contexts	"historical reconstruction" OR "heritage reconstruct*" OR "cultural heritage" OR "digital heritage" OR "virtual heritage" OR "museum" OR "storytelling"
Factors	"user experience" OR "engagement" OR "presence" OR "embodiment" OR "immers*" OR "interactiv*" OR "personaliz*" OR "adaptiv*"
Year of Publication	PUBYEAR > 2019 AND PUBYEAR < 2026

This combination ensured the inclusion of studies examining the technological implementation of MR and AI as well as their implications for user experience, engagement, and its use within historical and cultural heritage applications. The study selection process began with the formulation of the search string and the identification of an appropriate database. Following the execution of the search strategy, predefined inclusion and exclusion criteria were applied to filter the retrieved records and identify studies relevant to the research objectives. This review follows a structured and orderly screening process to ensure strict methods and relevant topics. Publications that did not align with the research focus were removed, while studies addressing the integration of MR and AI in historical reconstruction, heritage interpretation, museums, and related user experience factors were retained. The detailed inclusion and exclusion criteria are presented in Table 2.

**Table 2.** Inclusion and exclusion criteria for study selection

Include	Exclude
Specifically refers to Integration of Artificial Intelligence (AI) and Mixed Reality (MR), which is permitted within the XR concept.	Studies that do not address the integration of Artificial Intelligence (AI) and Mixed Reality (MR)
Articles written in English.	Papers in other than the English language.
Articles, books, reviews, book chapter and conference papers.	Studies of non-peer-reviewed journals, opinion or editorial papers.
Studies published in or after 2020.	Papers published before 2020.

Data retrieved based on the defined search string were downloaded and imported into Mendeley for reference management. Following data input into the Mendeley application, the data collection process was conducted through several systematic stages. The first stage involved reviewing the titles, abstracts, keywords, and conclusions of the retrieved studies. Subsequently, relevant information was extracted and organized in accordance with the focus of the review. Full-text analysis was then conducted when the preliminary information was deemed insufficient. This procedure was applied consistently across all included studies. The extracted data comprised author information, publication year, study type, and key research findings.

The analysis process focused on identifying how MR and AI technologies are applied to enhance user engagement and overall user experience in historical and cultural heritage settings. Articles were categorized and synthesized based on their thematic contributions, with particular attention given to interaction design strategies, adaptive or intelligent agents, and experiential storytelling mechanisms. The findings were summarized in tabular form to facilitate comparison across studies.

The study selection process is illustrated in Figure 1. Based on a search of the Scopus database, a total of 66 study records were identified. All retrieved articles were subsequently imported into Mendeley for reference management and initial screening, including the identification and removal of duplicate records. The results indicated that no duplicate articles were found. Next, title and abstract screening was conducted in accordance with the predefined inclusion and exclusion criteria, resulting in the exclusion of 20 articles. Articles that passed this stage were then assessed for full-text availability. However, 16 articles could not be accessed in full-text form. Consequently, 30 articles remained and were subjected to full-text screening, which led to the exclusion of an additional 9 studies that did not meet the inclusion criteria. Finally, 21 articles were selected for inclusion in the final systematic review.

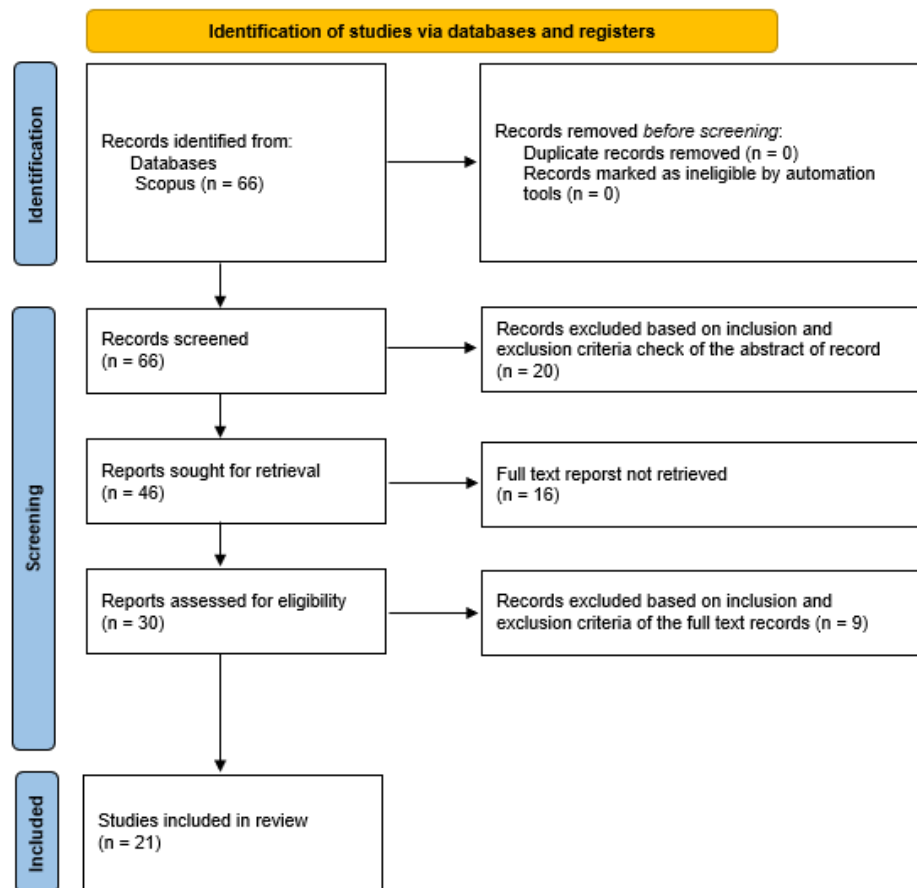


Figure 1. PRISMA flow chart

### 3. Proposed Model

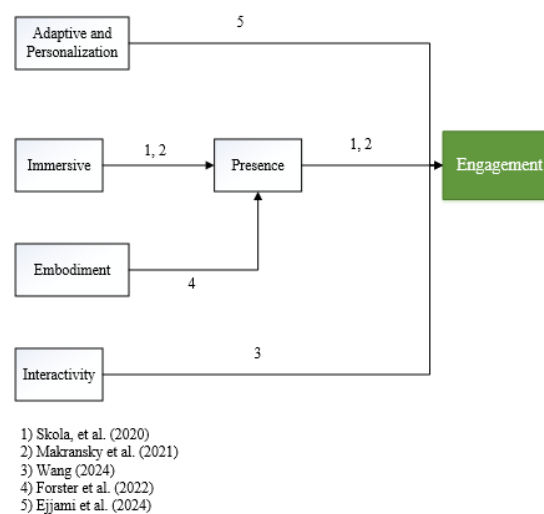
This study begins by constructing a model that connects several relevant theories related to enhancing user engagement in the use of Mixed Reality (MR) and Artificial Intelligence (AI). These theories are employed to derive factors that determine engagement enhancement and to serve as the conceptual basis for defining keywords in the Systematic Literature Review (SLR) process prior to the development of the conceptual model. The results of this integration of theories can be seen in Figure 2.

MR provides an immersive medium that enables users to experience environments closely resembling reality. When individuals are immersed in a virtual environment, the brain integrates information from multiple sensory modalities, including vision, audition, and touch. This process is known as multisensory integration. According to Implied Body Framework (IBF) theory, multisensory information indicates the presence of a body, referred to as the implied body (Forster et al., 2022). When multisensory integration functions effectively, the representation of the body becomes stronger. A stronger body representation subsequently leads to a heightened sense of presence, defined as the subjective feeling of truly being within the virtual environment. This theory further emphasizes that perspective plays a crucial role, as the viewing perspective determines the spatial reference point from which the virtual environment is perceived.

AI provides adaptive capabilities that allow systems to respond dynamically to change. According to Adaptive Personalization Theory (APT), developed by Ejjami (2024), AI-based learning systems capable of adapting instructional content in real time according to learner's abilities can enhance both motivation and engagement (Ejjami, 2024). The ability of AI to continuously assess learning progress and more precisely adapt to individual learner needs strengthens dynamic scaffolding, similar to a teacher providing real-time guidance. APT highlights that AI enables learning environments to become adaptive, personalized, and scalable.

A study conducted by Skola et al. (2020) examined a VR application that integrates two interactive VR elements, that is an underwater archaeological exploration and 360-degree video storytelling. The use of VR provides an immersive environment characterized by rich multisensory information. Such immersive experiences are believed to enhance the sense of presence. Through this approach, participants reported feeling present, engaged, and immersed in the VR experience (Škola et al., 2020). Consequently, the VR application delivers an immersive and compelling experience, increases user engagement, and stimulates brain activity associated with high levels of cognitive processing.

Interaction is a defining feature that differentiates immersive media from traditional, predominantly passive media. Wang's study investigated how different types of interaction, categorized into three dimensions, influence students' engagement levels. The findings revealed that learner-content interaction is the strongest predictor of engagement (Wang, 2024). This is because direct interaction with learning content helps reduce boredom and increase enjoyment. Therefore, it can be concluded that interaction with content plays a central role in fostering engagement.



**Figure 2.** Proposed MR-AI integration model

## 4. Result

This section presents the results of the systematic literature review, organized into two main aspects. The first sub-section provides a descriptive analysis of the selected studies, while the second sub-section examines the integration of Mixed Reality (MR) and Artificial Intelligence (AI).

### 4.1 Descriptive of Selected Study

The descriptive analysis comprised 21 selected studies, which were categorized based on authorship, publication year, study type, and key finding. Most of the studies were published between 2020 and 2025, reflecting the growing research interest in the integration of MR and AI for cultural heritage applications. Overall, the reviewed studies predominantly focused on the use of MR and AI technologies to enhance user experience in historical and cultural heritage contexts, including virtual museums and immersive storytelling. Most studies employed experimental or prototype-based evaluations, often combining user testing with qualitative feedback, while fewer studies developing conceptual study and systematic literature review. User experience related outcomes such as engagement, presence, immersion, interactivity and embodiment were the most frequently assessed variables, whereas fewer studies explicitly examined adaptive or intelligent system behaviors. This key finding of each study summarized in Table 3.

**Table 3.** Key finding for each study

No.	Author	Study types	Key finding
1	Bertocci et al. (2025)	Experimental Study	This study proposes an applied experimental workflow for cultural heritage preservation by integrating high-resolution photogrammetry, laser scanning, and Mixed Reality technologies to enable accurate 3D digitization, immersive visualization, and contextual interpretation of Michelangelo's unbuilt San Lorenzo façade, while exploring AI-based photogrammetric processing for enhanced accessibility and future hybrid methodologies.
2	Bronzin et al. (2021)	Conceptual Study	The study emphasizes that AI combined with MR plays a critical role in transforming traditional tourism into Smart Tourism. AI is used for automatic recognition of 2D and 3D objects (such as book pages, murals, museum artifacts) and linking them to rich multimedia content, while MR enables tourists to interact with these digital layers in real time.
3	Bronzin et al. (2022)	Methodology Proposal	The study concludes that integrating MR technologies with AI enables objective measurement of visitors' emotional responses, which can be used to personalize digital content and significantly enhance user experience in museum settings.
4	Chateauvert et al. (2025)	Conceptual Study	The study demonstrates that combining MR with AI that generated imagery enables a multisensory, interactive experience that reimagines sign language poetry through immersive spatial storytelling.
5	Constantinides et al., (2024)	Experimental Study	The integration of Large Language Models (LLMs) into Mixed Reality (MR) applications for virtual art exhibitions demonstrated a positive trend in enhancing user experience and perceived trustworthiness, although no statistically significant differences were observed compared to traditional interaction methods.
6	Guo et al. (2024)	Experimental Study	Integrating AI-driven interaction and MR significantly enhances user engagement, empathy, and cultural understanding in immersive Zen experiences.
7	Huang et al. (2025)	Explorative Study	Integrating AI-generated somatic hieroglyphs with mixed reality interaction fosters collective bodily awareness and reimagines language as an embodied, cross-cultural communication system.
8	Li et al. (2025)	Experimental Study	Integrating MR and Generative AI within an XR experience effectively blends real and imagined cultural heritage narratives, fostering user immersion and inspiring personal reinterpretations of urban heritage.
9	Xiong et al. (2025)	Experimental Study	Integrating AI-driven semantic animation with Mixed Reality transforms ephemeral sugar paintings into culturally authentic, interactive digital experiences that significantly enhance engagement and preservation.
10	Yang (2023)	Experimental Study	Integrating AI-generated content with mixed reality in cultural storytelling significantly enhances user engagement and cross-cultural understanding of intangible heritage.
11	Yannier et al. (2022)	Experimental Study	This study found that integrating AI-driven guidance with mixed-reality physical interaction significantly improves children's scientific understanding, engineering performance, and engagement compared to traditional unfacilitated exhibits.
12	Yu et al. (2025)	Systematic Literature Review	Integrating AI and MR in museums creates immersive, personalized, and interactive experiences that significantly enhance visitor engagement and learning outcomes.
13	Zhou & Globa (2025)	Conceptual and Experiment Study	This study integrating MR with optional haptics and lightweight Generative AI for asset creation. Integration of these technology can enhance perceived presence and engagement in remote storytelling for older adults, provided that simplicity, comfort, and adaptive workflows are prioritized.

No.	Author	Study types	Key finding
14	Pietroni (2025)	Concept Study, Literature Review, Experimental Case Studies	The study demonstrates that combining MR installations, such as holographic showcases and projection mapping, with AI-driven tools for audience profiling, content personalization, and predictive analysis significantly enhances visitor engagement, accessibility, and perceived authenticity, while introducing ethical challenges and sustainability concerns for long-term museum integration
15	Sung et al. (2022)	Experimental Study	In an MR retail environment, AI-embedded digital human storytelling significantly enhances immersion, learning, and satisfaction, which sequentially drives social sharing and purchase intentions through esthetic, entertainment, escapism, and educational experiences.
16	Teruggi et al. (2021)	Experimental Study	The study demonstrates that integrating AI-driven multi-level semantic classification of large-scale 3D point clouds with Mixed Reality environments enables efficient on-site visualization and interaction through HoloLens 2, significantly improving usability, computational performance, and real-time access to enriched cultural heritage data
17	Kourtesis (2024)	Systematic literature review	Integrating AI with MR enables multimodal, real-time adaptation (via gaze, hand/facial tracking, haptics, and biosignals like GSR/EEG) that can personalize training, therapy, and learning outcomes, but simultaneously amplifies privacy, cybersecurity, and manipulation risks, mandating robust ethical governance and regulation.
18	Belenioti & Kypri (2025)	Systematic literature review	Integrating MR with AI-driven personalization and guidance promises phygital, gamified, multisensory museum experiences that measurably elevate engagement, learning, accessibility, and value co-creation, yet empirical implementations in museums remain scarce and constrained by cost, digital skills, and maintenance requirements.
19	Dana & Yevgeniya (2025)	Systematic Literature Review	The review highlights that future integration of AI-driven personalization and analytics with Mixed Reality-based real-time 3D reconstruction is expected to significantly enhance educational engagement and accessibility by adapting immersive content to individual learners' needs while leveraging cloud rendering for scalability.
20	Wang (2024)	Experimental Study and Systematic Literature Review (SLR)	The integration of AI and MR through IVAR3M (VR + AR + PMR) enhances user satisfaction, information acquisition, and visitor engagement in digital museums, making the experience more interactive and immersive.
21	Sariman et al. (2024)	Systematic Literature Review (SLR)	The integration of MR with deep learning-based AI algorithms has the potential to create indoor navigation systems that are more accurate, interactive, and adaptive to complex environments, although it still faces challenges such as the need for large data and the limitations of MR devices.

#### 4.2 Integration of Mixed Reality and Artificial Intelligence

The reviewed studies collectively describe various approaches to integrating AI into the design of MR systems, where AI primarily serves as an enabling and supportive component within the overall MR architecture. In most cases, AI is employed to facilitate content generation, allowing for the automated creation of digital assets, narratives, and visual elements. AI in MR used to support personalized experiences tailored to individual user preferences and behaviors (Xiong et al., 2025; Yang, 2023; Zhou & Globa, 2025; Sung et al., 2022; Guo et al., 2024; Li et al., 2025; Huang et al., 2025). Additionally, several studies explore the use of AI in shaping or transforming virtual forms, contributing to more realistic and contextually appropriate representations within MR environments.

MR, on the other hand, is fundamentally utilized to merge virtual and physical spaces in a coherent manner, aiming to minimize cognitive confusion and maintain user's spatial and contextual awareness. The integration of AI further enhances this capability by enabling higher levels of interactivity within the MR environment. Intelligent agents can respond dynamically to user inputs, while adaptive virtual environments can adjust their behavior, content, or presentation in accordance with user's needs and interactions (Yannier et al., 2022).

Overall, the convergence of AI and MR introduces a novel paradigm in the design of immersive systems, particularly in the context of cultural heritage applications. By combining AI-driven adaptability and personalization with MR's spatial immersion, these technologies collectively contribute to richer, more engaging, and context-aware experiential outcomes. The key components of each supporting study are summarized in Table 4.

**Table 4.** Key components

No.	Author (year)	Key components
1.	Xiong et al. (2025)	<ul style="list-style-type: none"> <li>MR renders these AI-generated animations in an immersive environment using Meta Quest 3, enabling gesture-based interaction (grab, reposition, trigger animations) and creating a persistent digital gallery for cultural engagement.</li> <li>AI performs semantic recognition of sugar painting motifs (e.g., fish, butterfly, dragon) and maps them to culturally appropriate animation behaviors (<i>Fly, Swim, Walk, Jump, Grow</i>). This ensures authenticity and automates the animation process.</li> </ul>
2.	Yang (2023)	<ul style="list-style-type: none"> <li>AI uses LoRA fine-tuning on mythological illustrations to create generative models that replicate Silk Road artistic styles. Integrated into ComfyUI, it automates asset generation for XR environments and produces customizable patterns for interactive design.</li> <li>MR is developed with Unity and Apple Vision Pro, using spatial anchors for accurate alignment and realistic rendering. It includes interactive modules like assembling and texturing a Mythical Bird with AI-generated patterns, plus narrative scene exploration.</li> </ul>
3.	Yannier et al. (2022)	<ul style="list-style-type: none"> <li>AI uses depth-sensing cameras and computer vision to track children's actions and adapt feedback in real time. It provides interactive guidance through animated characters, supports learning with contrasting cases and self-explanation, and analyzes engagement metrics to assess effectiveness.</li> <li>MR combines a physical earthquake table with virtual feedback and gamified elements, enabling children to build towers, test stability under simulated shaking, and receive immediate digital cues that reinforce scientific concepts.</li> </ul>
4.	Zhou & Globa (2025)	<ul style="list-style-type: none"> <li>MR offers spatial slot-based layouts for organizing 3D objects, multimodal interaction (visual, auditory, haptic), and multiple input modes, from controllers to advanced haptic gloves, enhancing immersion and engagement despite usability challenges for older adults.</li> <li>Generative AI accelerates content creation through text-to-3D and image-to-3D tools, complemented by preset libraries. It uses scanning or 2D-to-3D conversion for complex or personal items, balancing speed with visual fidelity and usability.</li> </ul>
5.	Sung et al. (2022)	<ul style="list-style-type: none"> <li>MR creates immersive cultural spaces like augmented galleries, cafés, and historical houses, enabling visitors to explore Monet's garden, interact with digital content, and experience narrative journeys such as Van Gogh's life story without mobile devices.</li> <li>AI powers digital humans with voice interfaces, speech recognition, synthesis, and emotional expression, making interactions natural and conversational. These AI-driven characters deliver historical narratives and enhance engagement.</li> </ul>

No.	Author (year)	Key components
6.	Teruggi et al. (2021)	<ul style="list-style-type: none"> <li>MR applications run on HoloLens 2 using Unity3D and MRTK v2, enabling gesture-based and voice interactions for manipulating 3D objects. It supports dynamic resolution for global overviews and detailed inspections, applied in cultural heritage sites like Paestum, Milan Cathedral, and Bologna for tourism, education, and restoration.</li> <li>AI integrates machine learning and deep learning for 3D point cloud classification using a Multi-Level Multi-Resolution (MLMR) approach, organizing architectural elements hierarchically. This enables efficient handling of large datasets and detailed segmentation for complex structures.</li> </ul>
8.	Constantinides et al. (2024)	<ul style="list-style-type: none"> <li>MR uses HoloLens to integrate virtual paintings into physical spaces, creating immersive exhibitions with spatial navigation and voice-based interaction for exploring artworks and contextual information.</li> <li>AI leverages Large Language Models (LLMs) for real-time voice query processing, enabling natural, conversational responses about artworks through a client-server architecture using Django, OpenAI API, and Chroma DB.</li> </ul>
7.	Guo et al. (2024)	<ul style="list-style-type: none"> <li>AI powers dynamic randomization for unique visual effects, crushing simulations for tactile interactions, and motion capture with physiological computing to trigger symbolic responses based on gestures and calm states.</li> <li>MR creates a multimodal immersive environment by integrating projection mapping, spatial audio, and olfactory stimuli (e.g., sandalwood scent) to produce a sensory-rich experiential space. The MR experience is structured around four interactive scenarios, such as wandering, emergence, exploring and perfection.</li> </ul>
8.	Li et al. (2025)	<ul style="list-style-type: none"> <li>MR is developed using Unity3D, MRUK, and XR Interaction Toolkit on Meta Quest 3, enabling users to transition between VR and MR phases, interact with textured 3D models on a physical map, and experience enhanced presence through spatial integration.</li> <li>Generative AI (Stable Diffusion) converts user-created text prompts into visual content, allowing participants to generate images based on imagined past and future scenarios, which are then integrated into the XR experience.</li> </ul>
9.	Huang et al., (2025)	<ul style="list-style-type: none"> <li>MR, implemented on Meta Quest 3 with Unity and MRUK, overlays digital content onto a physical map of Hong Kong, creating embodied, multisensory representations of Urban Cultural Heritage sites. It supports interactive tasks, spatial placement of 3D models, and immersive engagement through visual, audio, and haptic cues.</li> <li>AI uses locally deployed generative models (Stable Diffusion) to create imaginative images and audio narratives based on participant-authored prompts, depicting ambiguous pasts and speculative futures of cultural heritage sites.</li> </ul>

## 5. Discussion

This systematic review highlights the integration of Artificial Intelligence (AI) and Mixed Reality (MR) in cultural heritage applications and examines their role in enhancing user engagement and overall experience. The findings underscore the importance of a conceptual model that connects four key dimensions, such as immersion, adaptivity and personalization, embodiment, and interactivity, as essential drivers of presence and engagement. This comprehensive model and its supporting literature are visually mapped in Figure 3.

In MR, immersion is strongly associated with presence, as higher immersion levels often lead to a more pronounced sense of “being there” in virtual or hybrid spaces (Rokhsaritalemi et al., 2020). While immersion describes the system’s objective attributes (e.g., sensory richness), presence reflects the user’s subjective psychological response (Ariya et al., 2025). Thus, immersion serves as a foundational condition that facilitates and strengthens the experience of presence. Immersion can be enhanced through content realism (Fan et al., 2022). Xiong et al. (2025) demonstrate that immersive MR experiences featuring animated sugar paintings dynamically instantiated within a configurable radius around the user, whose movement patterns are determined by AI-based semantic classification, significantly reinforce presence. This design allows users to perceive cultural objects as

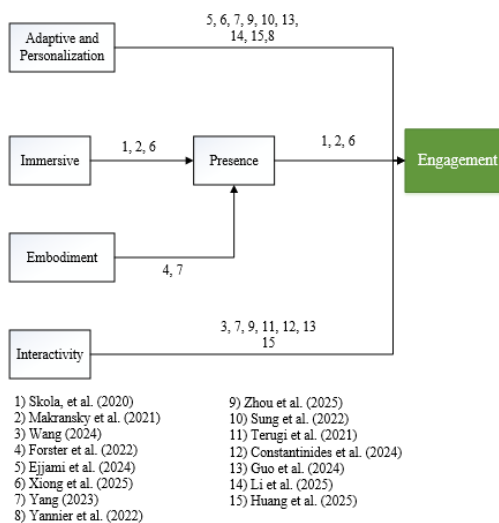
surrounding them rather than merely viewing static images. Furthermore, the study indicates that the presence of other agents within the virtual environment can also increase the sense of presence.

Adaptivity and personalization also play a crucial role in enhancing user engagement by allowing systems to respond dynamically to user inputs and contextual conditions. In this context, an adaptive system is defined as one that can adjust the environment in real time based on user behavior or preferences. Adaptive and personalized systems may be implemented through various approaches, including the generation of media content tailored to user preferences (Xiong et al., 2025; Yang, 2023; Zhou & Globa, 2025; Sung et al., 2022; Guo et al., 2024; Li et al., 2025; Huang et al., 2025) and the design of adaptive experiences (Yannier et al., 2022). Xiong et al. (2025) further report that the implementation of a virtual gallery interface allowing users to browse collections by animation type and modify animation parameters while maintaining the original semantic classifications, this adaptive experience encourages repeated interaction and promotes experience sharing among users (Xiong et al., 2025).

Embodiment in immersive environments refers to the degree to which users perceive a virtual body or representation as their own, encompassing sensations of body ownership, self-location, and agency over virtual actions (Forster et al., 2022). Study by Yang et al. (2023) revealed that embodiment enhances presence through natural interaction: "When a viewer extends their hand, the soaring bird hovers and lands gently upon it" (p.4), reinforcing physical involvement. Embodiment is influenced by the user's perspective within the environment. Yang et al.'s study expands embodiment beyond physical interaction to include perspective-taking, which significantly boosts presence and engagement. By positioning participants as active characters, the system shifts users from passive observers to narrative agents. This role-based perspective deepens presence because users perceive themselves as part of the story world rather than external viewers. Combined with embodied gestures, this design strategy strengthens the illusion of being physically and narratively situated within the environment. Consequently, perspective-driven embodiment amplifies engagement by fostering emotional and cognitive investment in the cultural narrative, supported by personalization and interactive modules that allow users to influence the unfolding experience.

Interactivity represents a reciprocal relationship between users and the system, enabling direct interaction with virtual objects and the physical environment to create dynamic and responsive experiences (Papadopoulos et al., 2021; Fan et al., 2022). In MR environments, interactivity can be classified based on interaction modalities, including visual-based (Yang, 2023; Zhou & Globa, 2025; Teruggi et al., 2021; Huang et al., 2025), audio-based (Zhou & Globa, 2025; Constantinides et al., 2024; Huang et al., 2025), haptic-based (Guo et al., 2024; Zhou & Globa, 2025), and sensor-based interactions (Papadopoulos et al., 2021; Zhou & Globa, 2025). Additionally, embodied interaction through gesture-based control supports engagement. This study employs hand-tracking functionality via Meta's Hand Tracking API to enable direct manipulation of semantically animated objects. Users can grab, reposition, or trigger animation sequences through natural gestures, and these interactions have been shown to enhance engagement, though further improvements are possible. Interactivity can act as a primary driver of user engagement, as narrative modules are designed to require users to interact directly with specific objects within each scene, which then triggers animations and advances the storyline (Yang, 2023). Overall, design elements such as high-fidelity immersion, embodied gestures, personalization through AI-generated content, and interactive storytelling work together to strengthen the connection between presence and engagement in cultural MR experiences.

Practically, this framework shows that integrating MR with AI's adaptive features allows museums to move away from fixed displays. By letting an intelligent system change stories and interactions based on what each visitor likes, heritage sites can create much more personal, fun, and engaging tours.



**Figure 3.** Conceptual framework with supporting literature

## Conclusion

The findings of this SLR underscore the urgency of integrating Mixed Reality (MR) and Artificial Intelligence (AI) to enhance user engagement through a conceptual model that connects four key dimensions namely, immersion, adaptivity & personalization, embodiment, and interactivity with presence and engagement. Immersion, as an objective condition, serves as the psychological foundation for presence. When content is realized dynamically and contextually, users experience a stronger sense of “being there” in virtual or hybrid spaces. Empirical shows that animated cultural objects instantiated around the user based on AI-driven semantic classification, along with the presence of other agents in the virtual environment, reinforce presence compared to static presentations. Furthermore, adaptivity and personalization, through preference-based content generation and adaptive gallery interfaces assisted by AI, encourage repeated interaction and experience sharing without compromising semantic integrity. Regarding embodiment, the consistency between body ownership, self-location, and agency is extended by perspective-taking approaches that position users as active narrative agents. The combination of embodied gestures with role-based storytelling deepens emotional and cognitive engagement with cultural narratives. Finally, cross-modal interactivity such as visual, auditory, haptic, and sensor-based along with hand-tracking for manipulating animated objects and narrative modules requiring user actions (such as touching objects to trigger animations or plot developments), acts as a direct driver of engagement. Overall, designs that integrate immersive fidelity, embodied gestures, AI-driven personalization, and interactive storytelling strengthen the presence and engagement connection in cultural MR experiences, while providing a robust foundation for an AI-MR integration model aimed at preservation, interpretation, and public participation in cultural heritage. This model can serve as a foundational model for developing MR and AI applications in cultural contexts, enabling the creation of immersive, adaptive, and interactive experiences that preserve and reinterpret heritage.

## References

1. Aloqaily, M., Bouachir, O., & Karray, F. (2023). Digital twin for healthcare immersive services: fundamentals, architectures, and open issues. In *Digital Twin for Healthcare* (pp. 39–71). Elsevier. <https://doi.org/10.1016/B978-0-32-399163-6.00008-1>
2. Ariya, P., Wongwan, N., Worragin, P., Intawong, K., & Puritat, K. (2025). Immersive realities in museums: evaluating the impact of VR, VR360, and MR on visitor presence, engagement and motivation. *Virtual Reality*, 29(3), 1–20. <https://doi.org/10.1007/s10055-025-01201-5>
3. Belenioti, Z. C., & Kypri, C. (2025). A Cutting-Edge Exploration: A Literature Review on Optimizing Museum Experiences Through Digital Transformation and VR Tour Software with 3DVista. *Springer Proceedings in Business and Economics*, 247–259. [https://doi.org/10.1007/978-3-031-87019-4\\_17](https://doi.org/10.1007/978-3-031-87019-4_17)
4. Bertocci, S., Bigongiari, M., & Pasquali, A. (2025). *Digitisation of the wooden maquette at Casa Buonarroti: A project never realised for the facade of San Lorenzo in Firenze*. 1–8. <https://doi.org/10.1145/3719236.3719260>



27. Papadopoulos, T., Evangelidis, K., Kaskalis, T. H., Evangelidis, G., & Sylaiou, S. (2021). Interactions in augmented and mixed reality: An overview. *Applied Sciences (Switzerland)*, *11*(18), 1–24. <https://doi.org/10.3390/app11188752>
28. Pietroni, E. (2025). Multisensory Museums, Hybrid Realities, Narration, and Technological Innovation: A Discussion Around New Perspectives in Experience Design and Sense of Authenticity. *Heritage*, *8*(4), 1–61. <https://doi.org/10.3390/heritage8040130>
29. Rokhsaritalemi, S., Sadeghi-Niaraki, A., & Choi, S. M. (2020). A review on mixed reality: Current trends, challenges and prospects. *Applied Sciences (Switzerland)*, *10*(2), 1–26. <https://doi.org/10.3390/app10020636>
30. Sariman, M. S., Othman, M., Akir, R. M., Mahamad, A. K., & Ab Rahman, M. A. (2024). A Review: Current Trend of Immersive Technologies for Indoor Navigation and the Algorithms. *Pertanika Journal of Science and Technology*, *32*(2), 955–977. <https://doi.org/10.47836/pjst.32.2.25>
31. Škola, F., Rizvić, S., Cozza, M., Barbieri, L., Bruno, F., Skarlatos, D., & Liarokapis, F. (2020). Virtual reality with 360-video storytelling in cultural heritage: Study of presence, engagement, and immersion. *Sensors (Switzerland)*, *20*(20), 1–17. <https://doi.org/10.3390/s20205851>
32. Sung, E. C., Han, D.-I., Bae, S., & Kwon, O. (2022). What drives technology-enhanced storytelling immersion? The role of digital humans. *Computers in Human Behavior*, *132*, 1–10. <https://doi.org/10.1016/j.chb.2022.107246>
33. Teruggi, S., Grilli, E., Fassi, F., & Remondino, F. (2021). 3D SURVEYING, SEMANTIC ENRICHMENT and VIRTUAL ACCESS of LARGE CULTURAL HERITAGE. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *8*(M-1–2021), 155–162. <https://doi.org/10.5194/isprs-annals-VIII-M-1-2021-155-2021>
34. Wang, B. (2024). The Application of Interactive Design Technology in Digital Intelligent Exhibition Display. *Computer-Aided Design and Applications*, *21*(S28), 296–308. <https://doi.org/10.14733/cadaps.2024.S28.296-308>
35. Xiong, H., Nie, K., Zeng, J., Shen, S., & Guo, M. (2025). *Animating the Ephemeral: Transforming Edible Cultural Heritage into Dynamic Digital Heritage through AI and Mixed Reality*. 1–8. <https://doi.org/10.1145/3743093.3771655>
36. Yang, S. (2023). Sentiment and Storytelling: What Affect User Experience and Communication Effectiveness in Virtual Environments? *Journalism and Media*, *4*(1), 1–12. <https://doi.org/10.3390/journalmedia4010003>
37. Yannier, N., Crowley, K., Do, Y., Hudson, S. E., & Koedinger, K. R. (2022). Intelligent science exhibits: Transforming hands-on exhibits into mixed-reality learning experiences. *Journal of the Learning Sciences*, *31*(3), 335–368. <https://doi.org/10.1080/10508406.2022.2032071>
38. Yu, T.-C., Huang, M.-X., Liu, Y.-H., Wu, H.-Y., Wang, B.-S., Tsai, H.-C., & Chien, S.-Y. (2025). A Systematic Review of Integrating Mixed Reality and Artificial Intelligence in Museums: Enhancing Visitor Experiences and Innovating Exhibit Design. *Proceedings of the Annual Hawaii International Conference on System Sciences*, 1533–1542. <https://doi.org/10.24251/hicss.2025.185>
39. Zhou, D., & Globa, A. (2025). *Social Connectedness in Older Adults: The Role of MR and Haptic Interaction in Remote Digital Storytelling*. 807–818. <https://doi.org/10.1145/3764687.3769932>