

International Journal of Human–Computer Interaction

ISSN: 1044-7318 (Print) 1532-7590 (Online) Journal homepage: www.tandfonline.com/journals/hihc20

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To cite this article: Nisanur Mercimek & Abdullah Bulbul (30 Sep 2025): Virtual Reality for Cultural Heritage: A Systematic Review and the Proposal of the AMUX-VR Framework, International Journal of Human–Computer Interaction, DOI: 10.1080/10447318.2025.2562962

To link to this article: https://doi.org/10.1080/10447318.2025.2562962

Published online: 30 Sep 2025.

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INTERNATIONAL JOURNAL OF HUMAN–COMPUTER INTERACTION
https://doi.org/10.1080/10447318.2025.2562962

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Virtual Reality for Cultural Heritage: A Systematic Review and the Proposal of the AMUX-VR Framework

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ABSTRACT

Virtual Reality (VR) has emerged as a valuable medium for cultural heritage, enabling immersive engagement with historical environments and narratives. Yet many heritage VR applications still lack adaptivity, personalization, and multimodal interaction, limiting their effectiveness for diverse audiences. This paper presents a systematic review of 44 studies published between 2018 and 2025 that examine user experience (UX) challenges in heritage VR, with a focus on navigation, interaction, and immersion. A thematic synthesis highlights five critical design dimensions that shape user engagement: adaptive navigation, multimodal sensory feedback, personalized content, dynamic storytelling, and intuitive interaction. Building on these insights, we introduce the AMUX-VR framework, an Adaptive Multimodal User Experience model designed to align heritage VR environments with user needs and behaviors. The framework provides a flexible, user-centered design strategy that enhances presence, usability, and educational impact across cultural tourism, education, and preservation contexts.

KEYWORDS

Virtual reality (VR); cultural heritage; user experience (UX); digital heritage; immersive environments

1. Introduction

In recent years, cultural heritage preservation has increasingly leveraged digital technologies, with Virtual Reality (VR) emerging as a powerful medium for immersive heritage experiences. VR allows users to explore museums, historical landmarks, and archaeological sites in virtual space, transcending physical and geographical limitations (Bozzelli et al., 2019; Paladini et al., 2019). Such digital experiences broaden accessibility and create new educational opportunities by enabling remote visits to heritage sites (Gonizzi Barsanti et al., 2015). As a technology that fully immerses users in a computer generated environment, VR can engage multiple senses simultaneously (Carmigniani & Furht, 2011). Studies have shown that incorporating audio, haptic, and other sensory inputs in virtual environments significantly enhances users' sense of presence and even their memory of the experience (Dinh et al., 1999). This multi-sensory immersion is especially valuable in cultural heritage applications, where realistic audiovisual and tactile feedback can convey the atmosphere of historical settings and artifacts more effectively than traditional media.

VR has rapidly become an essential tool for the preservation, presentation, and education of cultural heritage. Advances in 3D digitization techniques, such as photogrammetry and laser scanning, enable the creation of highly detailed virtual replicas of artifacts and monuments that users can examine interactively. For instance, dynamic virtual museum frameworks now allow cultural artifacts to be experienced in VR with high fidelity, greatly enhancing user engagement (Kiourt et al., 2016). Carrozzino and Bergamasco (2010) demonstrated that immersive VR installations in museum settings significantly enhance users' sense of presence and enjoyment. By leveraging multisensory interfaces and interactive environments, these exhibits enable contextual and engaging storytelling experiences that often surpass the communicative capacity of traditional static displays. Pietroni et al. (2013) demonstrated how VR techniques can support the digital reconstruction and contextual restoration of archaeological sites. In the Etruscanning project, a 3D model of the Regolini Galassi tomb was virtually recreated to reflect its

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original state in the 7th century BC, including the recontextualization of funerary goods. By visualizing heritage environments in virtual space, experts and the public can explore fragile or geographically remote sites without risking damage to the originals, overcoming many logistical and safety challenges of physical visitation (Bekele et al., 2018; Cassidy et al., 2019). VR thus not only preserves the visual and structural details of cultural heritage but also makes these riches accessible to a global audience irrespective of location.

Gonizzi Barsanti et al. (2015) demonstrated how VR-based presentations of ancient Egyptian funerary artifacts can support deeper public engagement through interactive exploration. Their work highlights the potential of low cost VR setups to increase accessibility and foster cultural understanding by allowing users to manipulate 3D models, reveal hieroglyphic translations, and explore symbolic meanings within a reconstructed ritual context. More recently, Eriksson et al. (2023) used immersive 3D reconstructions to recreate the layout of historical exhibitions at the Royal Palace in Stockholm. The study demonstrated how changes in display strategies and visual organization, analyzed across different time periods, can reveal curatorial narratives and visitor movement patterns. While the application is not fully VR-enabled, the first-person navigation and browsing modes offer valuable tools for analyzing spatial perception and historical display practices. These reconstructions highlight the scholarly potential of digital exhibitions in exploring alternative historical scenarios. The Paestum In VR project exemplifies how narrative-based virtual tours can attract and engage users by combining storytelling, interactive exploration, and spatial immersion. The application uses a guided experience, led by the digital character Ariadne, to present historical content in an emotionally compelling and educational format (Pagano et al., 2020). Such approaches harness VR's capacity for active user participation, which has been shown to increase enjoyment and interest in younger visitors. Beyond entertainment, VR also plays a role in public awareness and inclusion. Paladini et al. (2019) present a case study in which VR technology was employed to provide access to a culturally significant but physically inaccessible Buddhist temple in Myanmar. Samah et al. (2021) demonstrated that virtual museum applications can serve as effective alternatives during crises such as the COVID-19 pandemic, when physical visits are restricted. Their non-immersive VR system enabled users to explore cultural heritage content remotely, helping to sustain engagement and learning despite travel and access limitations. Moreover, Virtual reality (VR) facilitates the preservation and presentation of intangible heritage through immersive storytelling. The Sarajevo War Heritage VR project, for instance, combines narrative-driven content with interactive simulation to allow users to experience the historical context of the Sarajevo siege and the War Tunnel in a deeply engaging way (Rizvic et al., 2019). Similarly, Cantatore et al. (2020) demonstrated how integrating archival images and spherical 360° photographs into a virtual reconstruction of an archaeological site enhances both realism and immersion. The resulting environment allowed users to access and explore a physically challenging underground heritage space enriched with layered historical information and interactive media. While not focused on underwater or entirely lost sites, the study underscores how VR can offer meaningful access to otherwise inaccessible cultural spaces.

Despite the clear benefits of VR for cultural heritage, several challenges limit the effectiveness of current VR heritage applications. A prominent issue is motion sickness (cybersickness), a form of simulator sickness that some users experience in immersive environments which can cause disorientation and nausea, especially for novice users (Bekele et al., 2018). Usability and interface design remain key challenges in cultural heritage VR applications. Both Poux et al. (2020) and Lee et al. (2020) observed that novice or non-technical users often struggled with navigation and control schemes. In particular, Lee et al. (2020) reported instances of confusion and frustration when users interacted with unfamiliar VR controllers, highlighting the need for more intuitive and accessible design approaches. If interaction mechanisms and controls are not carefully designed for clarity and ease of use, the user's focus shifts from the content to struggling with the interface, undermining the educational or engagement value. Furthermore, Kersten et al. (2021) emphasize that high fidelity virtual reconstructions require substantial computational resources, and that the performance of VR applications is significantly influenced by both the resolution of the 3D models and the available hardware. Their tests demonstrated that maintaining a stable frame rate, ideally around 90 fps, is essential for immersive experiences, as lower frame rates can result in motion sickness and break the sense of presence. These findings underscore the need

to balance visual quality with technical feasibility when designing real-time VR heritage applications. These constraints often force developers to simplify models or environments, potentially reducing realism. Another shortcoming in many existing VR heritage applications is the lack of adaptivity or personalization. Most systems provide an uniform experience to all users, without accounting for individual differences in prior knowledge, interest, or comfort. In practice, museum visitors and learners are a heterogeneous group, what works well for one user (e.g., a gaming-oriented teenager) might not suit another (e.g., an older adult with limited VR experience). Javdani Rikhtehgar et al. (2023) conducted a user study that demonstrated how tailoring content to individual preferences in VR heritage exhibitions can significantly enhance user engagement and satisfaction. Their findings highlight that uniform information delivery may fall short of addressing diverse user needs, and that modeling user interests via behavioral cues such as gaze and viewing time, can support more personalized and meaningful experiences.

To address these limitations and unlock VR's full potential in cultural heritage, we propose a user centered framework based on adaptivity and multimodal interaction. Drawing on a systematic literature review (2018–2025), this study synthesizes design principles across five UX dimensions. While our systematic literature review focuses on studies published between 2018 and 2025, a limited number of earlier works are referenced when they represent seminal or foundational contributions to the field (e.g., Dinh et al., 1999; Sylaiou et al., 2010). The resulting framework—Adaptive Multimodal User Experience for Virtual Reality (AMUX-VR)—integrates adaptive navigation, multimodal feedback, AI-based personalization, interactive storytelling, and intuitive interaction mechanisms. This unified approach aims to improve inclusivity, engagement, and learning across diverse user groups. The following sections present the findings of the review and introduce the AMUX-VR model as a pathway toward more effective and accessible digital heritage experiences.

2. Methodology

This study follows a Systematic Literature Review (SLR) methodology to analyze and synthesize previous research on user experience and interaction in VR cultural heritage applications. The SLR process was structured in several stages, as detailed below.

2.1. Research questions

The review was guided by the following two research questions:

- RQ1: What key design elements in VR cultural heritage projects enhance users' sense of presence and immersion?
- RQ2: Which factors (e.g., interaction techniques, narrative approach, personalization) most strongly influence user engagement and learning in VR cultural heritage experiences?

By addressing these questions, the study aims to extract patterns and recommendations that can inform the design of future VR experiences in the cultural heritage domain.

2.2. Search strategy

We performed a comprehensive literature search across multiple academic databases, Scopus, Web of Science, IEEE Xplore, SpringerLink, and the ACM Digital Library, to gather relevant studies. This search targeted publications on VR applications in cultural and architectural heritage, with a particular focus on those exploring user experience evaluation and immersive interaction techniques (including digital reconstruction of heritage sites or artifacts). The search queries combined keywords across three dimensions: the technology (e.g., "VR" OR "Virtual Reality"), the application domain (e.g., "Cultural Heritage" OR "Architectural Heritage"), and the specific focus area (e.g., "User Experience" OR "Reconstruction"). For example, one query string was: ("VR" OR "Virtual Reality") AND ("Cultural Heritage" OR "Architectural Heritage") AND ("User Experience" OR "Reconstruction"). To ensure we

captured recent developments in the field, we limited the search to studies published between 2018 and 2025. This timeframe coincides with the period after advanced VR hardware became widely available (mid-2010s onward), which saw a surge of interest in applying VR to heritage contexts. All search results were then filtered using predetermined inclusion and exclusion criteria (detailed in Section 2.3) to ensure that only relevant, high-quality studies were selected for review. This systematic search strategy yielded a robust set of publications for subsequent analysis.

2.3. Inclusion and exclusion criteria

Following initial screening and application of inclusion/exclusion criteria, a total of 44 studies were retained for analysis.

Inclusion criteria required that a study: (1) specifically focused on VR applications in the cultural heritage domain (e.g., virtual museums, archaeological site tours, heritage education tools), and (2) incorporated some form of user experience assessment or interactive user engagement in its evaluation. We also confined the review to peer reviewed journal articles and conference papers published in 2018 or later and written in English, to maintain a contemporary and consistent academic scope. Exclusion criteria were applied to filter out works that fell outside our focus. We excluded studies that did not directly involve VR—for instance, research centered on related technologies like AR/MR or on purely technical aspects of digital heritage (such as 3D modeling or LiDAR scanning) without any user experience analysis. We also omitted papers that lacked empirical evaluation of a VR experience (i.e., no user study or usability testing), as well as non-peer reviewed sources (unpublished reports, theses, or articles not available through academic databases). Applying these inclusion and exclusion criteria narrowed the pool to a core set of studies most pertinent to our research questions.

2.4. Data extraction and analysis

After conducting a systematic literature review, the selected studies were analyzed based on their relevance to VR-based cultural heritage applications. The methodological process was structured in several stages, as illustrated in Figure 1, which depicts the workflow of the systematic literature review. The data extraction process was structured to identify key themes and trends in this field. The extracted information was categorized according to the following criteria:

- Study information: Authors, publication year, and type of publication (peer-reviewed journal article or conference paper).
- Research focus: Studies focusing on topics such as user experience, interaction mechanisms, navigation systems, immersion, presence, or gamification.
- VR application Details: the cultural heritage context (museum exhibit, archaeological site, etc.), the content of the VR experience, and any specific technology used (hardware like HTC Vive/Oculus, software platforms, etc.).
- User experience factors: Evaluation criteria related to user experience, including usability, interaction, and accessibility findings.
- Interaction and navigation methods: Techniques used to facilitate user interaction within VR environments.
- Key findings: Summary of results regarding user experience (such as usability scores, participant preferences, observed issues like motion sickness) and any conclusions or best practices the authors

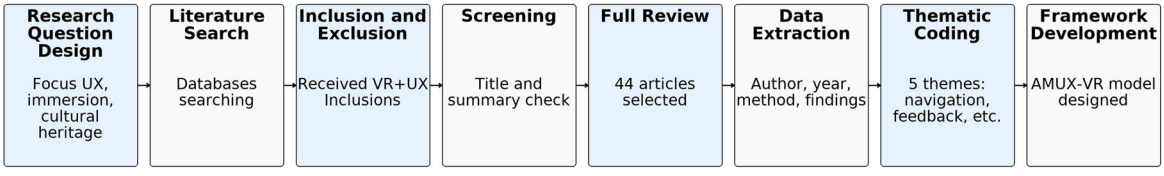

Figure 1. Systematic literature review workflow.

noted (e.g., "including a virtual guide improved visitor engagement" or "realistic textures enhanced presence at the cost of performance").

The extracted data were then analyzed by grouping studies with similar themes (e.g., studies focusing on navigation aids in VR heritage, studies on storytelling and narrative, studies evaluating educational outcomes). This thematic analysis enabled us to identify trends and consensus in the literature, as well as gaps and open questions. The findings are organized in the next section according to these themes, such as Interaction Mechanisms, Immersion and Presence, Storytelling/Gamification, Personalization, Evaluation Techniques, and Technical Challenges. We interweave insights from multiple studies under each theme to present a coherent overview of the state of the art and to answer the research questions posed.

The subsequent sections present the results of this analysis, including detailed discussions on user interaction techniques in VR heritage projects, the role of audio and guided narration, the impact of gamification and storytelling on user engagement, methods used for evaluating user satisfaction and learning, and the technical limitations encountered in current VR heritage applications, along with proposed solutions. Finally, we offer conclusions and recommendations for future research.

2.5. Thematic analysis

Through iterative coding and synthesis of the extracted data, five dominant thematic categories emerged. These categories reflect the core dimensions along which VR cultural heritage research has been advancing, and they formed the basis for how we organized our results and discussion. The five themes are:

1. Navigation and user interaction mechanisms: How users move through and interact with virtual heritage spaces. This theme covers navigation techniques (e.g., teleportation vs. free roaming), control schemes and interfaces (gamepads, motion controllers, gesture based inputs), and other interaction design choices that affect usability and user comfort in VR environments.
2. Multimodal sensory feedback and guidance: The use of multiple sensory modalities and guidance systems to enrich the immersive experience. Examples include audio components (narration and ambient sounds), visual cues or overlays (maps, arrows, virtual guides to aid orientation), and haptic feedback devices. Studies in this category examine how combining visual, auditory, and tactile feedback can heighten presence and understanding in a virtual heritage setting.
3. Interactive storytelling and gamification: Incorporating narrative driven experiences and game, like elements to engage users. This theme includes approaches like interactive storytelling with branching narratives, the integration of puzzles or challenges related to the cultural content, role playing scenarios, and gamified reward systems. Such elements are analyzed for their effectiveness in making cultural heritage content more compelling, educational, and enjoyable.
4. AI-driven personalization and adaptive learning: Tailoring the VR experience to individual users through artificial intelligence or adaptive algorithms. Studies in this area explore systems that adjust content difficulty, provide personalized learning pathways, or modify interface settings based on user preferences, behavior, or prior knowledge. The focus is on how personalization can improve user engagement and learning outcomes by delivering a more customized virtual heritage experience.
5. User interface design and information presentation: How information is delivered and interacted with via the interface, including layout clarity, iconography, menus, and content personalization.

It was common for an individual study to touch on multiple themes (for instance, a single project might discuss both interaction design and technical performance issues). By categorizing each study's contributions under these five thematic areas, we were able to compare similar findings across different projects and see how diverse research efforts align or diverge on each aspect. This thematic organization not only clarified the state of the art in each subtopic but also ensured that our synthesis addresses all parts of the research questions in a structured manner.

In the next section, we present our findings organized according to these themes, which provides a coherent narrative of current insights in VR-based cultural heritage design and evaluation. Furthermore, in our discussion, we integrate the lessons from all five themes to propose an overarching framework. In particular, the recurring design elements and user experience factors identified across the literature informed the development of an Adaptive Multimodal User Experience (AMUX-VR) framework, introduced later in the paper. This integrative framework synthesizes effective practices in navigation, multisensory feedback, storytelling, personalization, and usability into an unified approach. The goal of proposing the AMUX-VR framework is to build upon the collective insights of the systematic review and guide the creation of more immersive, engaging, and user-centered VR applications for cultural heritage.

3. User experience strategies for enhancing immersion and engagement in VR heritage

User experience (UX) and interaction mechanisms play a central role in the effectiveness of virtual reality (VR) applications for cultural heritage. Prior research highlights that engaging interfaces, contextually rich content, and immersive environments significantly influence user satisfaction and learning outcomes. For instance, Li and Kim (2023) applied the Kano-QFD model to evaluate user experience in handicraft ICH mobile applications. The study found that users placed the highest importance on interactivity, interface clarity, and culturally relevant content, factors that were strongly associated with improved satisfaction and engagement. These findings offer valuable insights for the design of meaningful user experiences in heritage-related digital platforms.

In virtual museum contexts, VR has been shown to enhance engagement by offering sensory immersion and interactive exploration, which strengthen users' emotional and cognitive connection to heritage sites. Concepts such as "presence" and "immersion" are especially relevant, as they determine how real and compelling the virtual environment feels. Sylaiou et al. (2010) found that users reporting a strong sense of presence also reported higher enjoyment, underscoring the relationship between realism and affective engagement. Similarly, Lee et al. (2020) observed that immersive and entertaining content not only elevated visitor satisfaction in a virtual museum but also increased their intention to visit the physical site.

Recent studies also emphasize the emotional and aesthetic impact of interactive design. Komarac and Došen (2022) demonstrated that digital exhibits with interactive elements significantly enhanced escapist and aesthetic experiences, which in turn boosted users' overall immersion. Guo et al. (2023) demonstrated that the combination of visual and auditory cues in digital museums significantly enhances visitors' sense of presence. Their findings highlight that these two modalities represent the most effective multisensory configuration for delivering immersive digital heritage experiences. On the technical side, Ghani et al. (2020) compared different levels of immersion—ranging from desktop to head mounted displays and concluded that while fully immersive VR offers stronger presence, spatial comfort and usability are equally crucial for user experience.

In addition to audiovisual immersion, physical interaction methods have proven effective in improving engagement. Popovici et al. (2022) developed a gesture-based VR system for museum settings, enabling users to explore and manipulate virtual artifacts using natural hand movements. Their user study with 137 participants showed that such touchless interaction enhanced engagement and was perceived as intuitive and easy to use. Likewise, Hulusic et al. (2023) observed that tangible user interfaces enhanced both immersion and learning by introducing tactile realism, enabling users to interact with virtual environments through familiar physical actions.

These insights have inspired more adaptive design approaches in cultural VR. Gong et al. (2024) developed a grounded theory-based model to evaluate user experience in virtual reality-based cultural heritage exhibitions. Their findings highlight how multisensory interaction, user control, and metacognitive engagement shape key experience dimensions such as learning, emotion, and ease of use. While immersive elements like visual, auditory, and task-based feedback enhance user involvement, the study also emphasizes tailoring exhibition types to visitor characteristics. Zhang et al. (2024) found that integrating game-like navigation tools, such as mini-maps and guided cues, improved spatial orientation and learning in virtual museums, reinforcing the idea that UX design should respond to users' cognitive and navigational needs.

Overall, the literature suggests that immersive virtual heritage experiences are most effective when interaction design, content delivery, and personalization are aligned. Thoughtfully integrated multimodal elements, visual, auditory, and tactile, help users engage more naturally with cultural content. At the same time, adaptive techniques that respond to individual behavior and preferences can enhance learning and enjoyment, making heritage applications more inclusive and impactful. These design considerations provide a strong foundation for the AMUX-VR framework proposed in this study, which integrates these dimensions into an unified, user responsive model for virtual cultural heritage experiences.

3.1. Navigation and spatial awareness in VR cultural heritage

In recent years, numerous studies have explored navigation methods and spatial awareness strategies in virtual reality (VR) applications for cultural heritage. These approaches aim to improve user comfort, orientation, and engagement by offering intuitive movement systems and spatial guidance tools. This section presents key findings from the literature, structured around the user impact of navigation techniques (e.g., teleportation, joystick, free movement), the role of mini-maps and guidance systems, and emerging adaptive solutions aligned with the AMUX-VR framework.

Teleportation has become the preferred navigation method in many VR heritage applications due to its ability to reduce motion sickness. Arrighi et al. (2021) found that teleportation was perceived as more comfortable and intuitive than continuous joystick-based movement, especially for novice users. However, teleportation may also lead to short-term spatial disorientation as users need time to reorient in their new position.

Overall, the literature suggests that joystick-based locomotion tends to increase simulator sickness, while teleportation improves comfort but may hinder spatial coherence. Physically walking is the most natural method but is limited by physical space. Therefore, combining movement styles—short-range physical steps with long-distance teleportation—has emerged as an effective compromise.

To support spatial awareness, VR heritage platforms increasingly use interface elements like mini-maps, visual markers, and guided navigation. Zhang et al. (2024) demonstrated that game inspired mini-maps with landmarks and directional arrows significantly improved users' spatial cognition and engagement. Wang et al. (2024) introduced MagicMap, an innovative 3D navigation system that combines 2D mini-map features with world-in-miniature (WiM) models. The system was shown to reduce cognitive workload and improve user experience in virtual museum environments by supporting intuitive wayfinding and prolonged engagement.

Bozzelli et al. (2019) proposed a layered guidance system that used visual cues and storytelling to help users navigate archaeological VR environments. The integration of interface-supported wayfinding with teleportation was shown to improve usability without reducing exploration freedom.

Voice guidance and virtual avatars have also been adopted to assist navigation and content delivery. Farella et al. (2022) proposed the design of a system that realizes an avatar with question-answering capabilities, for the specific purpose of giving help in immersive navigation of cultural heritage sites. Similarly, systems like the Invisible Museum (Zidianakis et al., 2021) used personalized content recommendations to guide visitors through large digital spaces.

Recent research supports the use of adaptive navigation systems that respond to the user's experience level. For example, beginner users benefit from guided teleportation or system suggested paths, while expert users prefer free exploration with fewer constraints. Arrighi et al. (2021) evaluated two distinct navigation methods as teleportation and menu-based jumping in a VR reconstruction of the Victoria Theatre. While both were found to be easy to use, menu based navigation was perceived as more intuitive and less physically demanding, especially for users less familiar with VR.

Studies have also proposed systems that dynamically adjust navigation based on real-time data such as movement patterns and interaction frequency. Troussas et al. (2025) integrated fuzzy logic into a VR museum system to dynamically adjust content complexity and guidance levels based on individual user profiles. This personalized approach aligns with the AMUX-VR model's goal of balancing comfort and engagement through adaptive navigation and user-specific interaction.

Chrysanthakopoulou et al. (2025) developed a multi-user MR system that allowed participants to explore virtual cultural heritage sites collaboratively through avatars. Their user evaluation highlighted that synchronous shared experiences significantly enhanced the sense of presence and engagement. While direct learning outcomes were not measured, users reported increased understanding and interest when engaging in collective exploration. Similarly, Bekele et al. (2021) observed that social interactions in mixed reality heritage scenarios promoted deeper engagement.

These findings suggest that integrating social exploration tools, such as shared pointers, chat functions, or synchronized tours, can increase orientation and spatial awareness, particularly in educational settings. Although not a standalone component in AMUX-VR, shared navigation can enhance several model elements, including interaction and personalization.

Literature from 2018 onward highlights several best practices for navigation and spatial awareness in VR-based cultural heritage applications:

1. Offer multiple locomotion modes (e.g., teleportation, guided path, free movement) to suit diverse user preferences.
2. Use mini-maps and visual markers to strengthen spatial orientation, particularly in complex environments.
3. Incorporate AI-powered guidance and user-adaptive navigation to tailor the experience to individual users.
4. Support social navigation where possible, enabling shared exploration to reinforce learning and presence.

These strategies are consistent with the AMUX-VR framework, particularly its emphasis on adaptive navigation and multimodal feedback. Implementing such techniques can improve user comfort, spatial awareness, and overall satisfaction in virtual heritage environments.

3.2. User interaction mechanisms and user engagement

Interaction mechanisms are essential for shaping user engagement in virtual cultural heritage applications. They determine how users navigate digital environments, interact with content, and form meaningful connections with cultural narratives. A well-designed interaction system not only improves usability but also encourages deeper involvement, especially in educational and exploratory contexts.

Studies comparing various interaction methods have consistently shown that more natural and intuitive approaches lead to higher satisfaction. Phichai et al. (2021) compared gesture-based, tangible, and VR controller-based interfaces in an interactive museum exhibit. While gesture-based inputs were perceived as novel, participants frequently reported difficulty with precision and control, which hindered interaction and reduced focus on learning content. In contrast, tangible interfaces, such as physical props and conventional controllers were more accessible, particularly for novice users. Popovici et al. (2022) demonstrated that Leap Motion-based hand tracking enabled users to interact directly with virtual exhibits through natural gestures. User feedback indicated that this form of touchless interaction enhanced engagement and was perceived as both intuitive and enjoyable. Similarly, Hulusic et al. (2023) found that tangible user interfaces (TUIs) enhanced realism and learning by allowing users to manipulate virtual artifacts with familiar physical motions.

These findings underscore the importance of aligning interaction mechanisms with human ergonomics and expectations. Interaction systems that support hand gestures, gaze-based selection, or voice commands can lower the learning curve for non-gamers and improve accessibility. Poorly implemented or overly complex systems, on the other hand, can break immersion and cause user frustration. Ensuring ease of use in manipulating objects, navigating menus, and triggering content is a core challenge for designers of cultural VR applications.

Beyond interface hardware, the nature of user interaction also influences engagement. Game-like tasks, branching storylines, and interactive narratives have been shown to motivate exploration and improve knowledge retention. Ivkovic et al. (2018) reported that a 360° storytelling experience helped users better understand historical context. Bozzelli et al. (2019) demonstrated that embedding

interactive narrative into archaeological sites increased learning motivation by adding purpose to exploration.

Social features also play a growing role in user engagement. Multi-user or collaborative VR applications allow participants to explore heritage spaces together, enhancing presence and fostering shared learning. Poux et al. (2020) found that collaborative navigation in a virtual heritage site improved both orientation and engagement. Bekele et al. (2021) demonstrated that collaborative and multi-modal mixed-reality experiences can significantly enhance cultural learning through real-time interaction between users. While the study focused on MR rather than full social VR, it highlights the potential of shared immersive environments for fostering engagement, communication, and meaningful museum experiences.

Škola et al. (2020) implemented a minimal, diegetic interaction model in which users explored a VR archaeological site freely and triggered contextual content, either 360° narrative scenes or audio, textual descriptions, by approaching specific points of interest. Interaction was facilitated through intuitive use of VR controllers, combining trackpad movement with trigger-based selection, while maintaining a seamless narrative flow. The system avoided traditional menus in favor of spatial cues like arrows and map pins, reinforcing immersion and guiding user attention without breaking presence.

Instead of real-time user interaction, Karuzaki et al. (2021) emphasized narrative immersion through pre-recorded gestures and motion-captured sequences, offering a sense of guided presence within both VR and AR environments.

In summary, interaction design in cultural VR should address both the technical and experiential aspects of user engagement. From ergonomic input methods to meaningful content and social collaboration, these components transform static digital environments into responsive and immersive learning spaces. This understanding directly supports the AMUX-VR model's emphasis on Interaction Optimization, which promotes accessible, enjoyable, and personalized engagement within virtual heritage applications.

3.3. Multimodal feedback and sensory immersion

A defining strength of virtual reality (VR) is its ability to stimulate multiple sensory channels, which in turn enhances users' sense of presence, the feeling of "being there" in the virtual environment. Presence and immersion are closely tied to the number of senses engaged and the fidelity of those stimuli. Foundational studies in psychology and HCI have shown that adding audio or tactile elements to visual VR environments significantly increases immersion and even memory recall (Dinh et al., 1999). In the context of cultural heritage, high-resolution visuals, realistic textures, and spatial audio cues can help reconstruct the atmosphere of historical sites, making experiences both emotionally engaging and educationally effective. For instance, Sylaiou et al. (2010) observed that virtual museum users reporting stronger presence also showed higher enjoyment and content engagement.

Recent work continues to emphasize the value of visual and auditory realism, but other sensory channels, particularly haptics, are increasingly recognized as essential for deepening immersion. Haptic feedback allows users to physically sense virtual artifacts, improving realism and reinforcing cultural understanding. Krumpen et al. (2022) demonstrated that haptic input significantly improved users' sense of realism and spatial engagement compared to visual-only experiences. Similarly, Antonya and Butnariu (2022) developed a custom haptic system that simulated the use of antique woodworking tools in a VR setting. User feedback indicated improved engagement and realism, suggesting that kinesthetic feedback, such as force and vibration, can contribute to understanding the physical behavior of heritage tools.

While multisensory design offers many benefits, it also poses performance and usability challenges. Developers must often strike a balance between visual fidelity and system responsiveness. High resolution meshes and advanced lighting can enhance realism but may increase hardware load, potentially leading to motion sickness or dropped frames. Kersten et al. (2021) conducted a comparative analysis of CAD based and mesh-based models in VR environments. While the high-detail mesh models provided more realistic visual representations, the CAD models, due to their lower polygon counts, enabled smoother performance and more stable frame rates, contributing to a more comfortable user experience

during navigation and interaction. Ghani et al. (2020) confirmed that immersive headsets significantly enhance users' sense of presence in virtual heritage environments. However, the study also found that user comfort and spatial perception are influenced by factors beyond display technology—such as clarity, cognitive load, and physical strain—implying the need for careful navigation and interaction design in VR applications.

The AMUX-VR framework incorporates these insights through its Multimodal Feedback component, which promotes the use of coordinated visual, auditory, and tactile cues to support different learning styles and sensory preferences. This approach not only enhances presence but also makes cultural VR more inclusive. Studies such as Agnello et al. (2019) exemplify how integrated visual, interactive, and navigational elements can enhance spatial understanding and user engagement in heritage environments. Sun et al. (2024) illustrates how multimodal VR systems, combining 3D visuals, ambient audio, and narrative voiceovers, can enhance spatial understanding and foster cultural empathy in heritage environments. The study highlights the importance of balancing sensory richness with usability, as well-designed multimodal systems can help bridge cognitive and emotional gaps between users and cultural content, creating more memorable and meaningful experiences.

3.4. AI-driven personalization and adaptive learning

As virtual heritage applications grow more sophisticated, personalization has emerged as a key strategy to improve user engagement and learning. Artificial intelligence (AI) technologies now enable dynamic adaptation of VR content based on user behavior, preferences, and learning pace. Rather than offering an uniform experience, adaptive systems adjust the level of detail, content path, and interaction style to suit each individual user.

Several recent studies highlight the effectiveness of AI-driven personalization. Farella et al. (2022) implemented a virtual museum guide using a BERT-based natural language model. The avatar answered user questions and adapted its responses, resulting in significantly higher engagement compared to static tours. Javdani Rikhtehgar et al. (2023) developed a VR exhibition system that dynamically tailored content delivery based on user gaze and interaction patterns. When users focused on specific painting elements, the system presented more detailed information about those aspects, while deprioritizing less relevant content. This real-time personalization improved both engagement and perceived relevance, as participants reported greater satisfaction when content aligned with their individual interests. In a similar vein, Troussas et al. (2025) developed SculptMate, a VR system using fuzzy logic to personalize task difficulty and provide adaptive guidance in a sculpture restoration simulation. Experimental results showed that users in the adaptive condition experienced greater learning gains and reported higher satisfaction with the overall experience. Zidianakis et al. (2021) enhanced a VR exhibition by recommending content based on user history, helping visitors discover exhibits aligned with their interests.

These examples illustrate how adaptive guidance, gaze-sensitive systems, and intelligent content recommendations can enrich the VR heritage experience. Personalized interaction encourages users to stay engaged longer and deepens their understanding of cultural material by aligning the experience with individual needs and interests.

The AMUX-VR framework reflects these insights through its AI-Based Personalization component. It supports the integration of intelligent feedback loops, tailoring content, navigation, and assistance, to create inclusive and user-responsive environments. As AI and VR technologies continue to evolve, adaptive learning will likely become a central feature of virtual heritage platforms, enhancing both educational value and user satisfaction across diverse audiences.

3.5. Interactive storytelling and gamified narratives

Within the AMUX-VR framework, Storytelling Adaptation refers to the dynamic tailoring of narrative elements in response to user input. This component plays a central role in enhancing engagement by embedding users into culturally rich, story-driven scenarios. In virtual heritage environments, combining interactive storytelling with gamification has proven to be a highly effective strategy for deepening

immersion and facilitating learning. Rather than acting as passive observers, users are encouraged to actively explore, make decisions, and progress through narratives that reflect real historical contexts (Argyriou et al., 2020). These approaches not only increase emotional investment but also improve spatial awareness and knowledge retention.

Gamified elements such as task-based progression, reward systems, and exploratory challenges have been shown to help sustain user interest in virtual heritage experiences. For instance, Bozzelli et al. (2019) demonstrated that embedding reward-based interaction into narrative-driven archaeological VR environments increased engagement and motivation. Li et al. (2023) conducted a bibliometric analysis of immersive technology in museum exhibitions and identified gamification as a key emerging trend. Their co-word analysis revealed that recent studies increasingly emphasize interactive storytelling and game-based strategies to improve user engagement and enhance visitor experience in virtual heritage contexts. For example, virtual museum experiences that include puzzles or side quests often report higher engagement than linear guided tours. Although guided tours offer structure, users often prefer the freedom to interact and explore at their own pace. This preference has led designers to incorporate open-ended mechanics and participant-driven tasks that shift the focus from passive observation to active problem solving.

The educational benefits of gamified storytelling are also well documented. Sun et al. (2024) developed a narrative-based VR experience centered on mural restoration, where users performed digital conservation tasks to better understand preservation practices. Arayaphan et al. (2022) developed a VR-based textile heritage experience using gamification elements such as object collection and scene progression. Their findings showed that participants engaging with the gamified 3D VR system demonstrated higher interest, learning outcomes, and satisfaction compared to the 360° exploration mode, suggesting the value of interactive and immersive design in cultural heritage applications.

Immersive storytelling also strengthens emotional connection and historical understanding. By placing users inside narrative arcs and enabling real-time interaction, VR heritage projects can create a "living history" effect. For instance, Sun et al. (2024) developed a simulation of the Dunhuang Mogao Caves where users participated in a restoration storyline, leading to deeper cultural awareness. Participant feedback emphasized the need for branching narratives that adapt to choices, rather than fixed linear stories. This highlights the value of adaptive narrative systems that adjust to individual interests and decisions, aligning with the goals of AMUX-VR's storytelling module.

Bozzelli et al. (2019) found that allowing users to influence the progression of the narrative enhanced their emotional engagement and motivation. While spatial orientation was not directly measured, the interactive structure encouraged active exploration and user agency. Cantatore et al. (2020) used archival imagery and 360° video to embed historical data within the story environment, which enhanced realism and user immersion. These cases underscore the importance of interaction in narrative construction (whether through choice, media integration, or freedom of movement as a mechanism for increasing presence and meaning).

Karuzaki et al. (2021) developed character-driven virtual narrators for a cultural heritage setting, focusing on natural human voice and subtle facial expressions to foster empathy and presence in storytelling.

Importantly, the synergy between storytelling and gamification has been identified as the best practice in virtual heritage design. Argyriou et al. (2020) introduced a branching storytelling framework in a gamified 360° cultural heritage tour, where users could select different exploration paths. Evaluation results showed that combining narrative design with interactive tasks enhanced both user engagement and learning. Similarly, Zhang et al. (2024) demonstrated that integrating game-inspired mini-map design elements, such as interactive controls, visual guidance, and informative overlays, significantly improved users' spatial cognition, immersion, and presence in virtual museum environments. These findings show how gamification principles, when thoughtfully applied, can enhance both engagement and educational value.

In the Bridges of Sarajevo project (Ivkovic et al., 2018), users explored 360° video-based narratives of historical bridges in a freely navigable format. Each completed story segment unlocked a puzzle piece, culminating in a final narrative sequence once all segments were viewed. This structure rewarded

exploration and encouraged full engagement with the content, striking a balance between narrative coherence and user agency, an approach that implicitly addresses the narrative paradox often encountered in interactive media. Similarly, the InHeritage project (Srdanović et al., 2024) implemented a choice-based learning path involving gamified and narrative elements. Longitudinal data revealed that users who interacted with the story and completed challenges reported stronger interest and retention of cultural information.

Selmanović et al. (2020) utilized a first-person, character-driven narrative within a 360° VR video to immerse users in the experience of a war tunnel. By avoiding external narration and instead relying on spatial progression to unfold the story, the study enhanced users' sense of presence and emotional engagement. Similarly, Škola et al. (2020) demonstrated that embedding structured 360° storytelling into explorable VR environments can effectively facilitate the communication of cultural heritage. Through the integration of immersive cinematic sequences and minimal, diegetic interaction techniques, their system promoted contextual understanding while maintaining narrative coherence. These findings suggest that hybrid approaches, blending spatial interactivity with embodied storytelling, offer a compelling framework for enhancing both user experience and cultural learning in virtual heritage settings.

In summary, adaptive storytelling and gamified interaction play a critical role in transforming VR heritage content into a deeply immersive and educational experience. Allowing users to influence narrative direction enhances engagement, while goal-oriented tasks encourage continued interaction and active learning. These findings strongly align with the AMUX-VR model's Storytelling Adaptation component, which emphasizes narrative flexibility and user-centered design. Collectively, the evidence supports the conclusion that responsive, story-driven experiences represent one of the most powerful tools for advancing user involvement and learning in virtual heritage contexts.

3.6. Information presentation and user interface design

Eriksson et al. (2023) emphasized that users' ability to explore and compare artworks within reconstructed historical spaces is a key aspect of meaningful engagement in digital heritage environments. Their system featured both walk-through and browse modes, enabling different forms of spatial interaction. While traditional UI elements like text panels or animated narratives were not employed, the design demonstrates how interface structure and visual layout directly shape user perception and exploration strategies.

Studies indicate that users are most interested in historical and social context, the artist's intent, and the stories behind the characters depicted in artworks. A significant positive correlation (Spearman correlation: $r = 0.658$) has been found between user interest and the time spent examining artifacts. Therefore, integrating information graphs and user interest models is recommended to create a more personalized user experience (Javdani Rikhtehgar et al., 2023).

User interface design is crucial for usability and learning efficiency in VR-based cultural heritage projects. User feedback highlights that some control mechanisms are difficult to use, and interfaces should be made more intuitive (De Paolis et al., 2022). Drossis et al. (2018) employed Leap Motion-based gesture control for interacting with 3D cultural heritage objects in a VR environment. Poux et al. (2020) noted that while their Leap Motion-based system enabled natural hand interaction with virtual objects, it exhibited tracking limitations, particularly when the user's palm was oriented vertically. This limitation highlighted the need for improved gesture recognition to ensure smoother interactions. Additionally, the authors emphasized interface simplification to avoid overwhelming users, suggesting that complex menu designs may hinder the learning process.

Phichai et al. (2021) compared Gesture-based, Tangible, and VR controller interfaces in an interactive learning exhibit. Results from the User Experience Questionnaire (UEQ) and semi-structured interviews showed that both VR and Tangible interfaces offered a more effective and satisfying user experience than Gesture-based input, which was rated poorly due to its lack of precision and usability. The findings emphasize the importance of developing more intuitive interaction methods for future VR applications.

Platforms like the Invisible Museum aim to create user-centered, collaborative, and dynamic 3D virtual exhibitions, developed in line with human-centered design (HCD) principles. Personalized content recommendations and semantic narratives are recognized as key elements that enhance user experience (Zidianakis et al., 2021).

Tangible User Interfaces (TUI) offer a more natural and effective interaction method within virtual environments. In the School House Virtual Museum (SHVM) project, TUI was found to significantly enhance user experience and immersion, reinforcing VR's potential in educational settings (Hulusic et al., 2023).

Mini-map designs and visual guidance elements help improve spatial cognition, reduce disorientation, and enhance user experience (Zhang et al., 2024). In the virtual reconstruction of Victoria Theatre, a menu-based navigation system was found to be more intuitive, while teleportation-based navigation provided users with a greater sense of control (Arrighi et al., 2021).

In conclusion, user-friendly information presentation and effective UI designs make cultural heritage more accessible and immersive in VR environments. Personalization of content, improved spatial navigation systems, and the adoption of intuitive interfaces significantly enhance user experience.

The effective use of information presentation and UI design directly impacts user satisfaction and learning performance in VR cultural heritage applications. For instance, the ArkaeVision VR project in Paestum, Italy, applies a narrative storytelling technique to actively engage users. Using HTC Vive headsets, participants virtually explore Poseidonia in the 5th century BC, guided by a digital character named Ariadne. Interactive temple artifacts, short texts, animations, and engaging visual storytelling have been shown to enhance spatial perception and user engagement with content (Pagano et al., 2020).

Research highlights that exhibition layout, visualization techniques, and UI design directly influence user engagement (Eriksson et al., 2023). Therefore, alternative historical scenarios and adaptive exhibition layouts should be explored to improve virtual presentations.

The study of Selmanović et al. (2020) interface design avoided traditional menus, opting instead for diegetic quiz prompts that maintained immersion and blended seamlessly with the spatial storytelling context.

Tangible User Interfaces (TUI) have demonstrated great potential in enhancing VR cultural heritage applications. For example, the School House Virtual Museum (SHVM) project integrated physical buttons and haptic interactions, which improved user experience and immersion in educational settings (Hulusic et al., 2023).

Bollini (2017) critically examined how the interplay between aesthetic qualities and functional usability in web interfaces influences user satisfaction. The study highlights that visually appealing, well-structured UI components contribute not only to the usability but also to the perceived quality of digital experiences. While the work focuses on web interfaces, the concluding discussion opens a path for extending such principles to multimodal and immersive environments like VR.

Debailleux et al. (2018) conducted a study in Mons, Belgium, where a VR-based reconstruction of the historical town square allowed children to explore architectural heritage using intuitive gaze-based interaction. Interactive visual cues and audio-guided storytelling supported wayfinding and information access. Results showed improvements in landmark recognition and historical recall, especially among younger users, who found the user interface easy to use and engaging.

Improving VR accessibility and usability is a central goal in user interface design. Studies emphasize the importance of user-friendly menus, intuitive controls, and clear visual cues, such as icons and directional guides, for enhancing the user experience. Navigation techniques like teleportation and simplified menu systems have been shown to reduce confusion and support comfortable movement in virtual environments (Arrighi et al., 2021; Zhang et al., 2024).

Overall, effective information presentation and user interface design are critical to the success of VR-based cultural heritage applications. Future studies should focus on user feedback-driven design iterations, adaptive interfaces, and the continuous optimization of UI components to better meet user needs.

As summarized in Table 1, this table presents the key thematic findings and research gaps identified across recent VR cultural heritage studies. The themes were derived from a synthesis of user experience, interaction design, and adaptive system strategies reported in the literature.

Table 1. Summary of key findings and research gaps identified in VR-based cultural heritage literature.

Category	Key findings	Research gaps
Navigation and spatial awareness	Teleportation and UI-assisted navigation reduce motion sickness and improve spatial cognition. Mini-maps and guided navigation enhance orientation in virtual heritage sites. Multi-user VR experiences can improve spatial awareness.	Lack of adaptive navigation systems that adjust based on user experience levels. Limited research on how collaborative VR affects spatial memory in heritage settings.
Interaction mechanisms and user engagement	Gesture-based and tangible interfaces increase engagement but can be unintuitive for novice users. Haptic feedback enhances realism and presence. Gamification and interactive storytelling drive deeper engagement.	Few studies explore real-time adaptive interaction that adjusts complexity. Lack of empirical data on long-term retention in gamified heritage.
Information presentation and UI design	Clear, intuitive interfaces support usability and reduce cognitive load. Tangible and gaze-based inputs improve accessibility.	Limited research on interface personalization by user skill level. Overlooked effects of UI design on heritage knowledge retention.
Multimodal feedback and guidance	Multimodal feedback (haptics, spatial audio, visual cues) enhances presence. Environmental sound and virtual guides aid orientation and learning.	Most systems rely mainly on visual/audio channels. Need for adaptive feedback responsive to user behavior.
AI-driven personalization and adaptive learning	Personalized guides and adaptive content improve engagement. Gaze tracking and AI-based recommendation support learning.	Real-time storytelling adaptation remains underdeveloped. Ethical implications of AI-driven behavior tracking require more study.

4. The AMUX-VR model: An adaptive framework for immersive cultural heritage

Virtual reality (VR) technologies have introduced new ways of engaging with cultural heritage, offering interactive environments where users can explore historical content beyond the limits of physical space. However, despite the growing number of VR heritage applications, many still follow a static and generalized design approach. These systems often provide a single mode of navigation, a fixed sequence of content, and limited responsiveness to user preferences or expertise. As a result, users may experience frustration with unintuitive controls, disengagement due to rigid storytelling, or cognitive overload from complex interfaces. Such limitations hinder the potential of VR to deliver meaningful and personalized heritage experiences.

To address these challenges, there is a growing need for frameworks that prioritize user adaptability and responsiveness. The AMUX-VR model (Adaptive Multimodal User Experience for Virtual Reality) was developed to meet this need by offering a structured, user-centered design strategy tailored to immersive cultural heritage. The model integrates adaptive navigation, multimodal feedback, interaction personalization, dynamic storytelling, and interface optimization into a cohesive experience. Rather than assuming all users interact with VR in the same way, AMUX-VR proposes that systems adapt to each user—modifying how content is accessed, how guidance is provided, and how sensory feedback is delivered—based on behavior, preference, and context. This approach aims to improve engagement, learning, and comfort by aligning the experience with individual users instead of requiring users to adapt to the system.

As illustrated in Figure 2, the AMUX-VR framework is composed of five key design strategies that collectively support adaptive and immersive user experiences in virtual cultural heritage environments. The background scene exemplifies the type of heritage setting, such as ancient architecture, where the model could be effectively implemented.

4.1. Design principles of AMUX-VR

Table 2 summarizes the five core components of the AMUX-VR framework and their functional roles in enhancing user experience in virtual cultural heritage environments. Each component reflects a specific design strategy—ranging from adaptive navigation to personalized content delivery—that collectively supports more immersive, accessible, and user-responsive VR experiences.

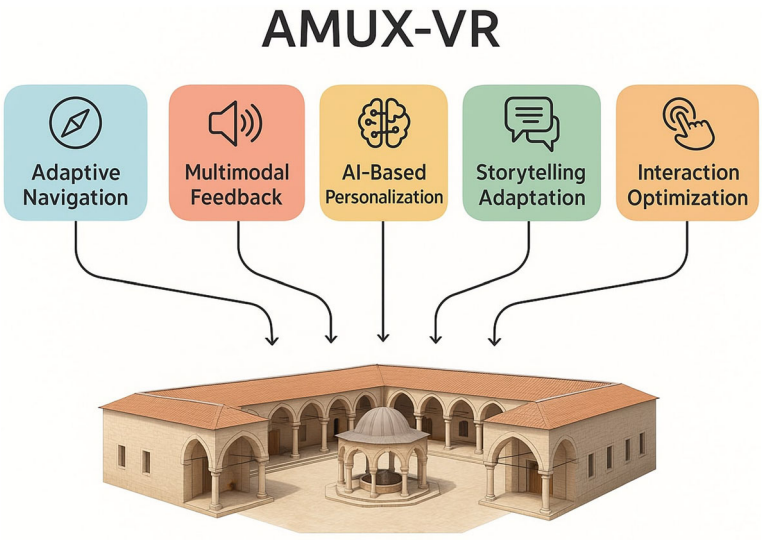

Figure 2. Visual representation of the AMUX-VR model, highlighting its five interconnected components: Adaptive navigation, multimodal feedback, AI-based personalization, storytelling Adaptation, and interaction Optimization. The bottom section contextualizes the framework within a virtual reconstruction of a cultural heritage site, illustrating its intended application environment.

Table 2. Comparison of AMUX-VR's components with existing approaches.

Component	Existing approaches	Innovations in AMUX-VR
Adaptive navigation	Standard navigation techniques (teleportation, joystick, or menu-based exploration) without real-time adaptation.	AI-driven navigation dynamically adjusts pathways based on user experience, optimizing movement efficiency and reducing disorientation.
Multimodal feedback	Haptic or spatial audio feedback implemented in isolation, with limited synchronization across modalities.	Integrates visual, auditory, and haptic feedback simultaneously, adjusting in real time based on user interaction patterns.
AI personalization	Basic recommendation systems provide limited user adaptation. Static content delivery remains the norm.	AI continuously monitors user engagement, dynamically adjusting difficulty levels and suggesting relevant historical content.
Storytelling adaptation	Predetermined branching narratives offer some level of interactivity but lack dynamic adaptation.	AI-driven storytelling personalizes narratives in real time based on user preferences, engagement duration, and gaze tracking.
User interaction	Fixed interaction methods (gesture-based, voice commands, or controllers) without adaptive adjustments.	User interactions are adapted dynamically, offering gesture-based, voice-controlled, or controller-driven input based on user preference.

The AMUX-VR model is grounded in core principles of user-centered design, aiming to provide a more inclusive and responsive experience for users of all backgrounds. Rather than presenting cultural heritage environments as static and one-directional, the model introduces adaptability as a foundational concept. Here, adaptability refers to the system's ability to respond dynamically to users' needs, preferences, and behaviors as they interact with the virtual space.

First, the model emphasizes personalization, recognizing that users enter virtual heritage environments with varying levels of experience, learning styles, and interests. A visitor well-versed in the historical subject matter may seek detailed, in-depth content, while a first-time user may prefer simplified narratives and guided exploration. AMUX-VR accommodates these differences by enabling systems to tailor navigation, content depth, and interaction complexity based on user input and real-time behavior.

Second, the model highlights the value of multimodality. Cultural heritage is inherently multisensory, shaped not only by sight but also by sound, movement, and touch. AMUX-VR encourages designers to incorporate multiple sensory channels: visual, auditory, haptic, and even olfactory where feasible, to support more immersive and memorable experiences. This principle acknowledges that users process information differently, and a rich sensory environment can enhance engagement and comprehension.

Third, AMUX-VR promotes interaction strategies that are both intuitive and accessible. Rather than relying exclusively on complex controllers or abstract menus, the model supports natural interaction methods, such as hand gestures, eye tracking, and voice input. These modalities reduce the learning curve and invite broader user participation, especially for audiences unfamiliar with gaming or digital systems.

Finally, AMUX-VR prioritizes narrative engagement and active exploration. It encourages developers to move beyond passive content delivery and build systems where users make choices, follow dynamic stories, and collaborate in shared virtual spaces. The combination of meaningful interactivity and personalized content delivery is central to the model's aim of fostering deeper cognitive and emotional connections with cultural heritage.

By integrating these design principles, AMUX-VR offers a flexible and scalable foundation for creating immersive VR heritage experiences that are both pedagogically effective and emotionally resonant. The following sections describe each of the model's five interlinked components in greater detail.

4.1.1. Adaptive navigation

While previous research has documented the effectiveness of various navigation techniques, such as teleportation, free-roam movement, and guided tours, in improving comfort and spatial orientation in virtual heritage environments, these approaches are often implemented as fixed design choices. The AMUX-VR model builds on this foundation by proposing Adaptive Navigation as a dynamic, user-responsive system. Rather than prescribing a single method for all users, this component aims to tailor movement and guidance based on individual preferences, experience levels, and real-time behavior.

Users enter VR environments with varying levels of familiarity and comfort. Novice users may prefer structured navigation features, such as on-screen prompts, guided paths, or teleportation modes that help minimize motion sickness. In contrast, experienced users often prefer greater autonomy through joystick-based movement or free roaming. Adaptive navigation reconciles these needs by offering systems that can switch modes or adjust progressively as users become more confident.

Empirical studies support the value of this flexibility. Arrighi et al. (2021) compared two locomotion methods, teleportation and menu-based navigation, in a virtual reconstruction of the Victoria Theatre. Their study found that while menu-based navigation was perceived as more natural and less physically and mentally demanding, teleportation provided greater precision and control, particularly when interacting with specific points of interest. De Paolis et al. (2022) implemented a teleportation-based navigation system in a virtual castle tour, allowing users to move intuitively between designated areas. This approach provided a low-demand locomotion method, making it suitable for general audiences. Zhang et al. (2024) further emphasized that visual aids, such as mini-maps and directional markers, significantly improved orientation when combined with appropriate navigation methods.

Importantly, adaptive systems can respond to user behavior in real time. For example, if a user frequently becomes disoriented or avoids certain areas, the system might offer additional guidance or simplify movement controls. Conversely, users who demonstrate confidence may receive less guidance and more exploratory freedom. This type of personalized support not only enhances comfort but also promotes deeper engagement by allowing users to focus on meaningful exploration rather than technical control.

As virtual heritage environments become more complex, adaptive navigation is increasingly essential for balancing immersion with accessibility. By adjusting interaction difficulty and respecting user preferences, this component enables smoother, more satisfying experiences. It also lays the foundation for responsive and inclusive VR heritage systems in alignment with AMUX-VR's broader goal of delivering user-centered immersive learning.

4.1.2. Multimodal feedback

Building upon adaptive navigation, the AMUX-VR model integrates multimodal sensory feedback to enrich immersion and deepen interpretive engagement with cultural heritage. Sensory input plays a central role in how users perceive and emotionally connect with virtual environments. In heritage settings, where meaning is often conveyed through spatial, auditory, and tactile elements, a single-sensory

interface may fail to fully represent the complexity of the experience. AMUX-VR encourages the use of visual, auditory, haptic, and where feasible, olfactory cues to activate multiple senses and support diverse learning styles.

Visual information remains the foundation of most VR heritage applications. High-fidelity 3D modeling, dynamic lighting, and smooth transitions allow users to grasp architectural form and spatial relationships. However, visuals alone may not be sufficient to maintain engagement or convey the atmosphere. Complementary auditory elements, such as ambient soundscapes or spatial narration, have been shown to heighten presence and improve orientation. For instance, Sun et al. (2024) demonstrated that integrating multimodal auditory cues, such as spatialized traditional background music and voice-guided narration, within the Dunhuang VR restoration enhanced users' cultural empathy and immersion by fostering emotional resonance and situated presence.

Haptic feedback provides an additional layer of realism, especially when users interact with artifacts or perform heritage-related tasks. Krumpen et al. (2022) showed that even basic tactile cues, such as vibration on touch, improved realism and task involvement in virtual museums. Hulusic et al. (2023) highlighted the benefits of tangible interaction tools in educational VR settings, noting that physical props such as desks and buttons enhanced user engagement and enjoyment. Although concept retention was not directly measured, the study's outcomes align with principles of embodied learning, suggesting that physical interaction may support cognitive engagement. Their findings further indicate that tangible user interfaces (TUIs) promoted higher participation and immersion, particularly among younger and less experienced users.

AMUX-VR treats sensory feedback as adaptable rather than static. The system can modulate the intensity, frequency, or type of feedback based on user behavior. For example, if a user hesitates or appears disengaged, the environment may amplify auditory cues or highlight interactive objects through subtle vibrations or pulsing effects. Conversely, for confident users, the system may reduce prompts to support more autonomous exploration. This responsiveness helps maintain focus and prevent cognitive overload, ensuring that feedback remains a support mechanism rather than a distraction.

Multimodal strategies also allow systems to accommodate individual preferences. While some users benefit from auditory instruction, others may prefer visual markers or kinesthetic input. AMUX-VR allows for parallel modalities, such as pairing spatial audio with haptic feedback or visual guidance, enabling users to engage in ways that align with their personal comfort and learning style. This flexibility broadens accessibility and supports sustained engagement across diverse audiences.

By adapting feedback to the user's behavior and needs, AMUX-VR promotes a more inclusive and personalized virtual heritage experience. Layered sensory input serves as a bridge between user and content, enhancing presence, aiding comprehension, and fostering emotional connection. Figure 3 presents an overview of the AMUX-VR framework and its five core components, including Multimodal Feedback, which collectively support immersive, user-centered design in cultural heritage VR.

4.1.3. AI-based personalization

As virtual cultural heritage applications grow in complexity and scale, it becomes increasingly clear that a one-size fits all approach fails to accommodate the diversity of users. The AMUX-VR model addresses this limitation through AI-Based Personalization, an adaptive layer that continuously adjusts content, navigation, and interaction strategies based on user preferences, behaviors, and skill levels. This component ensures that each user encounters a tailored experience that evolves in real time, enhancing both engagement and learning outcomes.

Recent studies have demonstrated the benefits of personalizing VR experiences through AI-driven methods. Javdani Rikhtehgar et al. (2023) explored the use of gaze tracking and behavioral analytics to determine user interest in a virtual exhibition. Their findings showed that users spent more time and



Figure 3. AMUX-VR model – block diagram.

reported higher satisfaction when content aligned with their preferences. Building on this insight, AMUX-VR proposes the integration of gaze data, voice input, and interaction patterns to dynamically adjust both the depth and presentation of content. For instance, a user showing sustained interest in a particular artifact may be provided with additional multimedia or contextual narration, while a user skipping rapidly through content might be guided toward key highlights.

Troussas et al. (2025) demonstrated how fuzzy logic and real-time user profiling could be used to modulate task difficulty and content complexity in a VR heritage learning system. Their platform, SculptMate, adapted to users' familiarity with the interface and prior knowledge, resulting in improved satisfaction and learning outcomes. AMUX-VR applies a similar logic by adjusting interaction complexity, such as simplifying interface menus for novices or offering advanced controls to more experienced users, based on ongoing user modeling.

Another significant aspect of personalization is intelligent guidance. Farella et al. (2022) presented a BERT-based virtual avatar designed to function as a cultural heritage guide within immersive VR environments. The avatar enables natural language interaction through speech recognition and synthesis, allowing users to ask questions about the site and receive spoken answers. While the system currently serves as a prototype, it demonstrates the potential for AI-driven guidance to enhance user engagement and provide contextualized information during virtual exploration. Likewise, Zidianakis et al. (2021) developed a recommendation engine within a virtual museum platform that provided personalized exhibition tours based on users' interaction behavior and preferences. This approach enhanced content discovery and engagement by tailoring experiences to individual curiosity.

AMUX-VR incorporates these personalization strategies through a modular system architecture. Behavioral data, such as time spent at exhibits, interaction frequency, and navigation patterns, can be analyzed to prioritize content and refine user pathways. In learning environments, this supports progressive educational flows that adapt in complexity over time. In exploratory settings, it allows for optional content branches or deeper dives that reflect varying user interests and engagement styles.

In addition to engagement, personalization supports inclusivity. Users with different cognitive or physical abilities may benefit from customized content pacing, simplified interfaces, or alternate interaction modes. A responsive system that adjusts narration speed, highlights key information, or offers assistive tools can help ensure broader accessibility. Importantly, AMUX-VR envisions personalization not just as a reaction to behavior, but also as a predictive mechanism, anticipating needs and proactively removing barriers before they occur.

By placing the individual at the center of the experience, AMUX-VR's AI-Based Personalization component transforms static heritage environments into evolving, user-aware spaces. This approach promotes deeper connection, longer engagement, and greater relevance: key outcomes for effective digital heritage interpretation and education.

4.1.4. Storytelling adaptation

In virtual cultural heritage applications, narrative is not only a tool for conveying information but also a means of fostering emotional connection and curiosity. Traditional storytelling methods in VR often follow linear paths, offering the same sequence and style of content to every user. While this structure may simplify delivery, it limits user agency and overlooks the potential of interactive media. The AMUX-VR model addresses this limitation by introducing Storytelling Adaptation, a dynamic approach in which the narrative structure, content depth, and delivery mode evolve based on user choices, interests, and interaction history.

Personalized storytelling allows each user to follow a journey that aligns with their motivations. For instance, a user drawn to architectural details may be guided through a narrative emphasizing design and construction techniques, while another may engage with human stories or social history. These variations are not pre-assigned but emerge through adaptive branching pathways, enabling the system to adjust emphasis, tone, or perspective as the user explores. This principle builds on findings from interactive media research, which suggest that users are more likely to retain information and feel immersed when they participate in shaping the narrative flow.

Ivkovic et al. (2018) implemented a 360° video-based storytelling application in the "Bridges of Sarajevo" project, where users explored individual narratives in a self-directed sequence. The system employed a puzzle-based reward mechanism that encouraged exploration and unlocked a final story upon completion. User feedback indicated that this narrative interactivity improved engagement and helped contextualize the historical significance of the bridges, demonstrating the pedagogical value of interactive storytelling in virtual heritage environments. Bozzelli et al. (2019) similarly demonstrated that embedding interactive story elements in a virtual archaeological site increased users' motivation to learn.

Recent works highlight the importance of adapting narrative delivery to the user's perspective and behavior. For instance, Selmanović et al. (2020) employed a first-person, character-driven narrative to foster empathy and immersion, allowing users to experience a historical event through the protagonist's eyes. Similarly, Škola et al. (2020) structured storytelling around spatial progression, where users triggered narrative scenes by physically exploring a virtual archaeological site. These adaptive techniques align with the AMUX-VR approach by personalizing storytelling flow through embodied navigation and contextual responsiveness.

AMUX-VR integrates storytelling adaptation by analyzing user preferences and adjusting narrative structure accordingly. Through behavioral cues such as topic selection, time spent at certain exhibits, or user questions posed to virtual guides, the system can infer which aspects of the story are resonating. It can then adapt by offering deeper elaboration, shifting narrative tone (e.g., more descriptive or analytical), or introducing new thematic threads. This responsiveness enhances immersion and makes the experience feel more personal and alive.

Adaptive storytelling also supports accessibility. Users with different learning styles or language proficiencies may benefit from different narrative modes, such as visual timelines, simplified summaries, or audio-based narration. AMUX-VR allows the story to shift format and pacing based on these preferences, without disrupting the continuity of the experience. In educational contexts, the system can modulate narrative complexity to align with learning goals, gradually building knowledge or reinforcing key concepts as users progress.

The critical design challenge in adaptive storytelling lies in maintaining coherence and authenticity. Cultural heritage content demands respect for historical integrity and nuance. AMUX-VR addresses this by anchoring adaptive narratives within curated content sets that ensure factual accuracy, while allowing flexibility in how that content is sequenced and framed. The aim is not to fictionalize history, but to let users engage with it from different angles that match their curiosity and background.

By supporting branching narratives, responsive dialogue, and modular story elements, AMUX-VR transforms passive content consumption into an active narrative journey. This shift enhances both cognitive engagement and emotional resonance, making cultural learning more memorable and meaningful.

4.1.5. Interaction optimization

Effective user interaction is essential for accessibility, usability, and overall satisfaction in virtual cultural heritage experiences. As users engage with complex digital environments, their ability to intuitively control and interact with content directly influences their sense of presence and immersion. The Interaction Optimization component of the AMUX-VR model focuses on reducing cognitive barriers and improving input mechanisms, making VR environments more inclusive and adaptable to diverse user needs.

Unlike traditional game environments, cultural heritage applications attract a wide range of audiences, many of whom may have limited familiarity with VR systems or gaming controls. For this reason, interaction design must accommodate varying levels of digital literacy. AMUX-VR emphasizes the need to implement multiple input modalities, including gesture-based interaction, gaze-based selection, voice-based commands, tangible controllers, and standard VR input devices, to ensure that users can interact with virtual content in ways that are perceived as natural and intuitive.

Studies have shown that interface complexity often becomes a barrier to engagement, especially for novice users. Phichai et al. (2021) evaluated gesture-based, tangible, and VR controller interfaces in a

museum learning context. While gesture-based interaction was perceived as innovative, users frequently found it difficult to control and unreliable. In contrast, tangible interfaces, where physical objects were used to interact with virtual content, were rated as more intuitive, particularly by participants with limited VR experience.

Similarly, Popovici et al. (2022) demonstrated that integrating Leap Motion-based hand tracking into a museum VR application enabled users to interact with artifacts using familiar physical gestures. Participants reported increased comfort and enjoyment, emphasizing the intuitiveness of the system and its potential to reduce the learning curve while enhancing engagement. Hulusic et al. (2023) reinforced this view through their work in educational VR environments, showing that tangible user interfaces (TUIs) increased participation and immersion among young and inexperienced users.

AMUX-VR builds on these insights by proposing adaptive interaction schemes that evolve in response to user behavior. For example, the system may initially guide users with simplified input options and visual prompts. As confidence grows, additional features, such as voice navigation or multi-object manipulation, can be gradually introduced. The model also supports fallback options, enabling users to choose between modalities based on their physical capabilities or preferences. This flexibility is particularly important in inclusive design, where accessibility considerations are critical for supporting users with motor impairments, cognitive differences, or language-related barriers.

By optimizing interface usability and offering multimodal interaction pathways, AMUX-VR ensures that users spend less time learning how to interact and more time engaging with content. It also fosters a greater sense of agency, as users are empowered to interact in ways that align with their personal strengths and comfort levels. These design choices contribute not only to individual engagement but also to the system's overall scalability across diverse audiences and settings.

Together with the other components: Adaptive Navigation, Multimodal Feedback, AI-Based Personalization, and Storytelling Adaptation, Interaction Optimization completes the AMUX-VR framework. These interconnected elements function as a cohesive system, shaping an immersive, personalized, and inclusive virtual heritage experience that responds dynamically to user input and context. The next and final section reflects on how this model supports current design needs and offers a roadmap for future VR heritage applications.

4.2. Application of the AMUX-VR framework in a virtual heritage scenario: Everyday life in the Ottoman Empire

To demonstrate the practical integration of the AMUX-VR framework, we propose a conceptual scenario: a Virtual Reality museum experience titled "Everyday Life in the Ottoman Empire." This VR application aims to support cultural education and digital tourism by allowing users to explore a reconstructed 16th-century Ottoman neighborhood, including a mosque, market (bazaar), school (medrese), and domestic interiors. Each component of the AMUX-VR model plays a distinct role in shaping the user experience.

4.2.1. Adaptive navigation

Upon entry, users complete a brief interaction assessment that determines their experience level and goals (e.g., tourist, student, researcher). Beginners are offered guided teleportation navigation with UI assistance and virtual signs, while experienced users can freely explore using joystick control. The system can transition between modes as users demonstrate increased confidence.

4.2.2. Multimodal feedback

The environment delivers layered sensory input to enhance presence. Spatial audio captures the ambient sounds of the bazaar (voices, footsteps, animal carts), while haptic cues (through controllers or gloves) simulate physical interaction with textiles, architectural elements, or tools. Visual indicators highlight points of interest or provide navigational guidance as needed.

4.2.3. AI-based personalization

A virtual assistant (e.g., a historical character or curator avatar) delivers content dynamically adapted to the user's preferences and interaction history. For example, if a user spends more time in the Medrese area, the assistant offers deeper insights into Ottoman education and manuscript culture. Gaze duration and object selection inform real-time content adjustments, including narration pace and thematic focus.

4.2.4. Storytelling adaptation

The exhibit embeds an interactive storyline that follows the life of a fictional artisan navigating through Ottoman daily life. Users participate in historically grounded scenarios, such as preparing for a religious festival, negotiating in the marketplace, or transcribing texts in a scriptorium. These narratives branch based on user decisions, with outcomes and information shaped by choices made during the journey.

4.2.5. Interaction optimization

Interaction options include hand-tracking, gaze-based selection, and voice commands, allowing accessibility across user demographics. Children and elderly users can interact without relying on controllers, while advanced users can enable full gesture-based exploration. Interface complexity adapts dynamically, menus are simplified for novices and expanded with advanced filters for researchers.

This scenario is summarized step-by-step, showing how each AMUX-VR component is activated during the user's experience. By aligning the virtual environment with individual user needs and preferences, the system supports learning, exploration, and emotional engagement with intangible and tangible aspects of historical heritage.

While existing VR applications often remain static, AMUX-VR allows a museum application to adapt to the needs of both a young gaming enthusiast and an older cultural tourist. This will increase user satisfaction and learning.

5. Limitations and future work

While the AMUX-VR framework presents a comprehensive and flexible approach to designing adaptive VR experiences for cultural heritage, several limitations should be acknowledged. First, the framework remains conceptual and has not yet been tested through empirical implementation or user studies. Although it is grounded in a systematic review of current literature, real-world deployment in museums or educational settings is necessary to evaluate its practical value and adaptability across different user groups.

Second, the personalization strategies proposed, such as gaze tracking, behavioral modeling, and real-time adaptation, require access to advanced input technologies that may not be available in all contexts. Implementing rich sensory feedback or dynamic narrative branching may also exceed the capabilities of standard consumer VR systems, especially in resource-constrained institutions.

Third, although the model emphasizes inclusivity and accessibility, it currently does not offer specific design strategies for users with disabilities, such as those with visual or cognitive impairments. Future work should explore how AMUX-VR can integrate universal design principles and assistive technologies to expand its reach.

Ethical considerations are another important area for development. AI-driven personalization depends on collecting behavioral data, such as gaze patterns and interaction logs, which raises concerns about privacy, transparency, and user consent. Future implementations should therefore follow privacy-by-design practices, incorporating strategies such as data minimization, anonymization or pseudonymization of user data, and local processing where feasible. Ensuring explicit user consent and providing clear, accessible information about data usage will also be essential to uphold trust and align with legal data protection standards.

Recognizing the conceptual nature of the AMUX-VR framework, future research will prioritize the development of prototype virtual environments that systematically embed its adaptive navigation, multimodal feedback, AI-based personalization, storytelling adaptation, and interaction optimization modules. A preliminary pilot study is envisaged within the forthcoming 6–12 months to evaluate usability and perceived immersion across small user cohorts. The insights derived from this exploratory phase

will inform the design of a more comprehensive experimental campaign, anticipated within 12–18 months, thereby facilitating robust empirical validation of the framework's efficacy in enhancing user experiences in virtual cultural heritage contexts.

Looking ahead, pilot deployments in real-world environments, such as immersive exhibitions, virtual classrooms, or mobile platforms, can provide valuable insights into the strengths and limitations of the framework. Comparative testing with existing systems, along with user satisfaction assessments and learning outcome analysis, will help refine the model. In addition, evaluating AMUX-VR across different platforms (e.g., mobile VR, WebXR) could improve its accessibility and scalability.

Addressing these challenges through iterative testing, ethical safeguards, and inclusive design will allow AMUX-VR to evolve into a robust, user-centered toolset for next-generation digital heritage applications.

5.1. Evaluation plan

To assess the practical effectiveness of the AMUX-VR framework, future research should apply both qualitative and quantitative evaluation methods. Controlled user studies in museum or classroom VR settings can compare AMUX-VR-based designs with baseline systems that lack adaptive or multimodal features.

Key user experience metrics may include presence (via the Presence Questionnaire), usability (System Usability Scale), cognitive load (NASA-TLX), and learning outcomes such as task performance and knowledge retention. Behavioral analytics, like navigation paths, gaze patterns, and interaction frequency, can offer additional insights into engagement and interaction quality.

Post-experience surveys and interviews can capture subjective impressions, including emotional connection, perceived personalization, and overall satisfaction. Studies should involve participants with varied experience levels, age groups, and digital literacy to evaluate the model's inclusiveness.

Testing across different application domains, such as educational VR platforms, mobile-based heritage apps, or museum installations, can also inform the model's adaptability and scalability. Through this multi-faceted evaluation, the AMUX-VR framework can be refined into a validated foundation for designing personalized, immersive cultural heritage experiences.

6. Conclusion

This study explored the evolving role of Virtual Reality (VR) in cultural heritage by conducting a systematic literature review focused on user experience, interaction techniques, and immersive design strategies. The findings reveal that effective navigation, multimodal feedback, adaptive storytelling, and personalized guidance are key to increasing presence, learning, and engagement in VR heritage applications.

In response to the limitations observed in many existing systems, such as static interfaces, one-size-fits-all interaction designs, and limited support for user diversity, we propose the AMUX-VR framework. This model offers a structured, user-centered approach that combines five critical dimensions: Adaptive Navigation, Multimodal Feedback, AI-Based Personalization, Storytelling Adaptation, and Interaction Optimization. Together, these components allow VR experiences to dynamically adjust to users' skills, interests, and behavior, offering a more inclusive and meaningful engagement with cultural content.

By integrating these adaptive and multimodal strategies, AMUX-VR addresses challenges such as motion sickness, usability barriers, and limited personalization, factors often cited as obstacles in the adoption of VR for heritage settings. The framework supports both educational and exploratory applications, whether in museums, virtual field trips, or remote access to otherwise inaccessible heritage sites.

Future research and implementation efforts can expand upon this work by testing the AMUX-VR model in real-world settings, such as through pilot studies in virtual museums or educational platforms. As VR technologies continue to evolve, frameworks like AMUX-VR can guide designers and cultural institutions in delivering more responsive, engaging, and human-centered digital heritage experiences.

As future implementations progress, it will be essential to incorporate explicit privacy-by-design safeguards, including data minimization, anonymization or pseudonymization, and local processing strategies. These measures ensure that AI-driven personalization within the AMUX-VR framework aligns with ethical standards and legal data protection requirements, thereby fostering user trust and supporting responsible deployment in virtual cultural heritage environments.

Acknowledgements

The authors would like to thank the anonymous reviewers for their constructive comments that helped improve the manuscript. The authors also acknowledge the use of OpenAI's ChatGPT for language enhancement and clarity suggestions during manuscript preparation. All content was reviewed and approved by the authors.

Disclosure statement

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

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References

Agnello, F., Avella, F., & Agnello, S. (2019). Virtual reality for historical architecture. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLII-2/W9*, 9–16. https://doi.org/10.5194/isprs-archives-XLII-2-W9-9-2019

Antonya, C., & Butnariu, S. (2022). Preservation of cultural heritage using virtual reality technologies and haptic feedback: A prototype and case study on antique carpentry tools. *Applied Sciences*, *12*(16), 8002. https://doi.org/10.3390/app12168002

Arayaphan, W., Intawong, K., & Puritat, K. (2022). Digitalization of ancient fabric using virtual reality technology at the Wieng Yong house museum: The FABRICVR project. *Digital Applications in Archaeology and Cultural Heritage*, *26*, e00233. https://doi.org/10.1016/j.daach.2022.e00233

Argyriou, L., Economou, D., & Bouki, V. (2020). Design methodology for 360 immersive video applications: The case study of a cultural heritage virtual tour. *Personal and Ubiquitous Computing*, *24*(6), 843–859. https://doi.org/10.1007/s00779-020-01373-8

Arrighi, G., See, Z. S., & Jones, D. (2021). Victoria theatre virtual reality: A digital heritage case study and user experience design. *Digital Applications in Archaeology and Cultural Heritage*, *21*, e00176. https://doi.org/10.1016/j.daach.2021.e00176

Bekele, M. K., Champion, E., McMeekin, D. A., & Rahaman, H. (2021). The influence of collaborative and multimodal mixed reality: Cultural learning in virtual heritage. *Multimodal Technologies and Interaction*, *5*(12), 79. https://doi.org/10.3390/mti5120079

Bekele, M. K., Pierdicca, R., Frontoni, E., Malinverni, E. S., & Gain, J. (2018). A survey of augmented, virtual, and mixed reality for cultural heritage. *Journal on Computing and Cultural Heritage*, *11*(2), 1–36. https://doi.org/10.1145/3145534

Bollini, L. (2017). Beautiful interfaces. from user experience to user interface design. *The Design Journal*, *20*(sup1), S89–S101. https://doi.org/10.1080/14606925.2017.1352649

Bozzelli, G., Raia, A., Ricciardi, S., De Nino, M., Barile, N., Perrella, M., Tramontano, M., Pagano, A., & Palombini, A. (2019). An integrated VR/AR framework for user-centric interactive experience of cultural heritage: The Arkaevision project. *Digital Applications in Archaeology and Cultural Heritage*, *15*, e00124. https://doi.org/10.1016/j.daach.2019.e00124

Cantatore, E., Lasorella, M., & Fatiguso, F. (2020). Virtual reality to support technical knowledge in cultural heritage. The case study of Cryptoporticus in the archaeological site of Egnatia (Italy). *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLIV-M-1-2020*, 465–472. https://doi.org/10.5194/isprs-archives-XLIV-M-1-2020-465-2020

Carmigniani, J., & Furht, B. (2011). Augmented reality: An overview. In B. Furht (Ed.), *Handbook of augmented reality* (pp. 3–46). Springer. https://doi.org/10.1007/978-1-4614-0064-6_1

Carrozzino, M., & Bergamasco, M. (2010). Beyond virtual museums: Experiencing immersive virtual reality in real museums. *Journal of Cultural Heritage*, *11*(4), 452–458. https://doi.org/10.1016/j.culher.2010.04.001

Cassidy, B., Sim, G., Robinson, D. W., & Gandy, D. (2019). A virtual reality platform for analyzing remote archaeological sites. *Interacting with Computers*, *31*(2), 167–176. https://doi.org/10.1093/iwc/iwz011

Chrysanthakopoulou, A., Chrysikopoulos, T., Arvanitis, G., & Moustakas, K. (2025). Reimagining historical exploration: Multi-user mixed reality systems for cultural heritage sites. *Applied Sciences*, *15*(5), 2854. https://doi.org/10.3390/app15052854

Debailleux, L., Hismans, G., & Duroisin, N. (2018). *Exploring cultural heritage using virtual reality* [Paper presentation]. Digital Cultural Heritage: Final Conference of the Marie Skl-Odowska-Curie Initial Training Network for Digital Cultural Heritage, Itn-Dch 2017, Olimje, Slovenia, May 23–25, 2017, Revised Selected Papers (pp. 289–303).

De Paolis, L. T., Chiarello, S., Gatto, C., Liaci, S., & De Luca, V. (2022). Virtual reality for the enhancement of cultural tangible and intangible heritage: The case study of the castle of Corsano. *Digital Applications in Archaeology and Cultural Heritage*, *27*, e00238. https://doi.org/10.1016/j.daach.2022.e00238

Dinh, H. Q., Walker, N., Hodges, L. F., Song, C., & Kobayashi, A. (1999). *Evaluating the importance of multisensory input on memory and the sense of presence in virtual environments* [Paper presentation]. In Proceedings IEEE Virtual Reality (Cat. no. 99cb36316), Houston, TX, USA (pp. 222–228).

Drossis, G., Birliraki, C., & Stephanidis, C. (2018). *Interaction with immersive cultural heritage environments using virtual reality technologies* [Paper presentation]. HCI International 2018–Posters' Extended Abstracts: 20th International Conference, HCI International 2018, Las Vegas, NV, USA, July 15–20, 2018, Proceedings, Part III 20 (pp. 177–183).

Eriksson, J., Widén, P., Ferrari, S., & Hayashi, M. (2023). Digital reconstructions of picture galleries as art historical method: The virtual museum at the royal palace in Stockholm. *Digital Applications in Archaeology and Cultural Heritage*, *29*, e00268. https://doi.org/10.1016/j.daach.2023.e00268

Farella, M., Chiazzese, G., & Bosco, G. L. (2022). *Question answering with Bert: Designing a 3D virtual avatar for cultural heritage exploration* [Paper presentation]. 2022 IEEE 21st Mediterranean Electrotechnical Conference (Melecon), Palermo, Italy (pp. 770–774).

Ghani, I., Rafi, A., & Woods, P. (2020). The effect of immersion towards place presence in virtual heritage environments. *Personal and Ubiquitous Computing*, *24*(6), 861–872. https://doi.org/10.1007/s00779-019-01352-8

Gong, Q., Zou, N., Yang, W., Zheng, Q., & Chen, P. (2024). User experience model and design strategies for virtual reality-based cultural heritage exhibition. *Virtual Reality*, *28*(2), 69. https://doi.org/10.1007/s10055-024-00942-z

Gonizzi Barsanti, S., Caruso, G., Micoli, L. L., Covarrubias Rodriguez, M., & Guidi, G. (2015). 3D visualization of cultural heritage artefacts with virtual reality devices. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XL-5/W7*, 165–172. https://doi.org/10.5194/isprsarchives-XL-5-W7-165-2015

Guo, K., Fan, A., Lehto, X., & Day, J. (2023). Immersive digital tourism: The role of multisensory cues in digital museum experiences. *Journal of Hospitality & Tourism Research*, *47*(6), 1017–1039. https://doi.org/10.1177/10963480211030319

Hulusic, V., Gusia, L., Luci, N., & Smith, M. (2023). Tangible user interfaces for enhancing user experience of virtual reality cultural heritage applications for utilization in educational environment. *Journal on Computing and Cultural Heritage*, *16*(2), 1–24. https://doi.org/10.1145/3593429

Ivkovic, I., Klisura, N., & Sljivo, S. (2018). Bridges of Sarajevo. In *Proceedings of the Central European Seminar on Computer Graphics* (pp. 107–114).

Javdani Rikhtehgar, D., Wang, S., Huitema, H., Alvares, J., Schlobach, S., Rieffe, C., & Heylen, D. (2023). Personalizing cultural heritage access in a virtual reality exhibition: A user study on viewing behavior and content preferences. In S. Berkovsky, I. Cantador, T. Mitrovic, & L. Chen (Eds.), *Adjunct Proceedings of the 31st ACM Conference on User Modeling, Adaptation and Personalization (UMAP '23)* (pp. 379–387). Association for Computing Machinery.

Karuzaki, E., Partarakis, N., Patsiouras, N., Zidianakis, E., Katzourakis, A., Pattakos, A., Kaplanidi, D., Baka, E., Cadi, N., Magnenat-Thalmann, N., Ringas, C., Tasiopoulou, E., & Zabulis, X. (2021). Realistic virtual humans for cultural heritage applications. *Heritage*, *4*(4), 4148–4171. https://doi.org/10.3390/heritage4040228

Kersten, T., Drenkhan, D., & Deggim, S. (2021). Virtual reality application of the fortress al Zubarah in Qatar including performance analysis of real-time visualisation. *KN - Journal of Cartography and Geographic Information*, *71*(4), 241–251. https://doi.org/10.1007/s42489-021-00092-1

Kiourt, C., Koutsoudis, A., & Pavlidis, G. (2016). Dynamus: A fully dynamic 3D virtual museum framework. *Journal of Cultural Heritage*, *22*(7), 984–991. https://doi.org/10.1016/j.culher.2016.06.007

Komarac, T., & Došen, O. (2022). Discovering the determinants of museum visitors' immersion into experience: The impact of interactivity, expectations, and skepticism. *Current Issues in Tourism*, *25*(22), 3675–3693. https://doi.org/10.1080/13683500.2021.1952941

Krumpen, S., Klein, R., & Weinmann, M. (2022). Towards tangible cultural heritage experiences—enriching VR-based object inspection with haptic feedback. *Journal on Computing and Cultural Heritage*, *15*(1), 1–17. https://doi.org/10.1145/3470470

Lee, H., Jung, T. H., Tom Dieck, M. C., & Chung, N. (2020). Experiencing immersive virtual reality in museums. *Information & Management*, *57*(5), 103229. https://doi.org/10.1016/j.im.2019.103229

Li, J., & Kim, K. (2023). Kano-QFD-based analysis of the influence of user experience on the design of handicraft intangible cultural heritage apps. *Heritage Science*, *11*(1), 59. https://doi.org/10.1186/s40494-023-00903-w

Li, J., Wider, W., Ochiai, Y., & Fauzi, M. A. (2023). A bibliometric analysis of immersive technology in museum exhibitions: Exploring user experience. *Frontiers in Virtual Reality*, *4*, 1240562. https://doi.org/10.3389/frvir.2023.1240562

Pagano, A., Palombini, A., Bozzelli, G., De Nino, M., Cerato, I., & Ricciardi, S. (2020). Arkaevision Vr game: User experience research between real and virtual Paestum. *Applied Sciences*, *10*(9), 3182. https://doi.org/10.3390/app10093182

Paladini, A., Dhanda, A., Reina Ortiz, M., Weigert, A., Nofal, E., Min, A., Gyi, M., Su, S., Van Balen, K., & Santana Quintero, M. (2019). Impact of virtual reality experience on accessibility of cultural heritage. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLII-2/W11*(W11), 929–936. https://doi.org/10.5194/isprs-archives-XLII-2-W11-929-2019

Phichai, P., Williamson, J., & Barr, M. (2021). Alternative design for an interactive exhibit learning in museums: How does user experience differ across different technologies-VR, tangible, and gesture. In *2021 7th International Conference of the Immersive Learning Research Network (ILRN)* (pp. 1–8). IEEE.

Pietroni, E., Pagano, A., & Rufa, C. (2013). *The Etruscanning project: Gesture-based interaction and user experience in the virtual reconstruction of the Regolinigalassi tomb* [Paper presentation]. 2013 Digital Heritage International Congress (Digitalheritage), Marseille, France (vol. 2, pp. 653–660). IEEE.

Popovici, D.-M., Iordache, D., Comes, R., Neamțu, C. G. D., & Băutu, E. (2022). Interactive exploration of virtual heritage by means of natural gestures. *Applied Sciences*, *12*(9), 4452. https://doi.org/10.3390/app12094452

Poux, F., Valembois, Q., Mattes, C., Kobbelt, L., & Billen, R. (2020). Initial user-centered design of a virtual reality heritage system: Applications for digital tourism. *Remote Sensing*, *12*(16), 2583. https://doi.org/10.3390/rs12162583

Rizvic, S., Boskovic, D., Bruno, F., Petriaggi, B. D., Sljivo, S., & Cozza, M. (2019). Actors in VR storytelling. In *2019 11th International Conference on Virtual Worlds and Games for Serious Applications (vs.-Games)* (pp. 1–8). IEEE.

Samah, K., Nasaruddin, N. I. S., Afandi, M. A. R., Rahim, N. Z. A., Rum, S. F. M., & Saman, F. I. (2021). Non-immersive virtual reality for Malay and Islamic world museum Melaka: Effects from covid-19 pandemic. *International Journal of Advanced Technology and Engineering Exploration*, *8*(74), 91–101. https://doi.org/10.19101/IJATEE.2020.S1762118

Selmanović, E., Rizvic, S., Harvey, C., Boskovic, D., Hulusic, V., Chahin, M., & Sljivo, S. (2020). Improving accessibility to intangible cultural heritage preservation using virtual reality. *Journal on Computing and Cultural Heritage*, *13*(2), 1–19. https://doi.org/10.1145/3377143

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*, *20*(20), 5851. https://doi.org/10.3390/s20205851

Srdanović, P., Skala, T., & Maričević, M. (2024). Inheritage—a gamified mobile application with AR and VR for cultural heritage preservation in the metaverse. *Applied Sciences*, *15*(1), 257. https://doi.org/10.3390/app15010257

Sun, T., Jin, T., Huang, Y., Li, M., Wang, Y., Jia, Z., & Fu, X. (2024). Restoring Dunhuang murals: Crafting cultural heritage preservation knowledge into immersive virtual reality experience design. *International Journal of Human–Computer Interaction*, *40*(8), 2019–2040. https://doi.org/10.1080/10447318.2023.2232976

Sylaiou, S., Mania, K., Karoulis, A., & White, M. (2010). Exploring the relationship between presence and enjoyment in a virtual museum. *International Journal of Human-Computer Studies*, *68*(5), 243–253. https://doi.org/10.1016/j.ijhcs.2009.11.002

Troussas, C., Papakostas, C., Krouska, A., Mylonas, P., & Sgouropoulou, C. (2025). Fuzzy-based virtual reality system for cultural heritage: Enhancing user interaction and experience through contextual assistive messaging. *International Journal of Human–Computer Interaction*, *41*(18), 1–19. https://doi.org/10.1080/10447318.2024.2443801

Wang, X., Li, Y., & Liang, H.-N. (2024). *Magicmap: Enhancing indoor navigation experience in VR museums* [Paper presentation]. 2024 IEEE Conference Virtual Reality and 3D User Interfaces (VR), Orlando, FL, USA (pp. 881–891).

Zhang, Y., Zhang, B., Jang, W., & Pan, Y. (2024). Enhancing spatial cognition in online virtual museum environments: Integrating game-based navigation strategies for improved user experience. *Applied Sciences*, *14*(10), 4163. https://doi.org/10.3390/app14104163

Zidianakis, E., Partarakis, N., Ntoa, S., Dimopoulos, A., Kopidaki, S., Ntagianta, A., Ntafotis, E., Xhako, A., Pervolarakis, Z., Kontaki, E., Zidianaki, I., Michelakis, A., Foukarakis, M., & Stephanidis, C. (2021). The invisible museum: A user-centric platform for creating virtual 3D exhibitions with VR support. *Electronics*, *10*(3), 363. https://doi.org/10.3390/electronics10030363

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