Embodied and Tangible Interaction in Collaborative Room-Scale Mixed Reality: Insights from a Visitor Experience in a Cultural Heritage Context

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Figure 1: Visitors interacting with tangible replicas in a multi-user Mixed Reality cultural heritage experience.

Abstract

The rapid expansion of eXtended Reality (XR) technologies, particularly collaborative room-scale Mixed Reality (MR), has created opportunities for shared virtual experiences that blend real and virtual environments, allowing multiple users to interact and engage collaboratively. This paper presents an evaluation of a cultural heritage MR application, focusing on two key aspects: embodied interaction and tangibility. Embodied interaction was enabled through free movement and tactile engagement with co-present participants. Tangibility was facilitated by allowing visitors to handle replicas of ancient artifacts and interact with physical elements that aligned with their virtual counterparts. Drawing on insights from a study involving 73 visitors, the paper highlights how these elements contributed to the overall experience, fostering immersion, collaboration, and deeper engagement with cultural content. By focusing on visitor perspectives and presenting qualitative findings, this study aims to advance understanding of the impact of tangibility and embodiment in collaborative MR experiences within cultural heritage contexts.

Index terms: mixed reality, tangibility, embodiment, room scale, cultural heritage context.

1 Introduction

eXtended Reality technologies are increasingly recognized as powerful tools for enhancing user experiences across diverse domains, including cultural and recreational contexts. Immersive Mixed Reality, a subset of XR, blends real and virtual environments to enable users to interact with digital content while engaging with their physical surroundings. Included within the broader definition of MR are capabilities such as free-form movement in larger physical spaces, natural gesture-based interactions, multi-user functionality, and multimodal sensory experiences, including audio, haptics, vibrotactile feedback, and even unconventional modalities like temperature, wind, taste, and smell [17].

Room-scale MR, characterized by its support for physical movement and natural interactions, has seen some application in gaming (with location-based entertainment attractions such as The Void[1]), training, simulation, architecture, healthcare, and collaborative work. Although still nascent in cultural heritage and archaeology, MR holds significant promise for enhancing visitor engagement and learning [12]. Cultural institutions are beginning to explore how immersive and interactive experiences can expand their appeal to broader demographics, with a growing emphasis on multimodal and multisensory engagement to attract visitors of all ages and backgrounds.

This paper examines two critical aspects of MR—embodied interaction and tangible engagement with physical spaces and objects—within the informal learning context of a cultural heritage center or museum. The study draws on a qualitative evaluation of a custom MR installation deployed in a cultural space, designed to support immersive experiences through the use of headsets, simultaneous participation for up to five co-located visitors, and device-less interaction enabled by hand and motion tracking. Visitors could interact with tangible physical objects while experiencing multisensory stimuli, including smell and wind. Tailored for institutions open to a broader public, the system offers a low-cost, adaptable solution suitable for spaces of varying sizes. Deployed in a prominent cultural institution in a European capital city, this installation has been in active use by the general public, engaging visitors of all ages. The findings presented in this paper focus on visitor experience, highlighting the specific

[1] https://en.wikipedia.org/wiki/The_Void_(virtual_reality)

contributions of embodiment and tangibility to engagement and learning within this cultural heritage context.

2 Background and Related Work

2.1 Mixed Reality and Cultural Heritage

Mixed Reality applications in cultural heritage are still emerging but have shown great potential for transforming visitor experiences by blending the physical and digital realms. Bekele et al. [1] developed a cloud-based collaborative and multi-modal MR application for virtual heritage, emphasizing the integration of multiple sensory modalities to create immersive and interactive learning environments. Their work highlights the importance of collaboration and co-located experiences in fostering deeper cultural engagement. Building on this, Bekele et al. [2] examined the influence of collaborative MR on cultural learning, revealing that multi-user interaction significantly enhances understanding and retention of cultural knowledge. Their findings emphasize the role of MR in promoting social interaction and collective discovery within heritage contexts. Broader surveys offer reviews of the state of AR, VR, and MR in cultural heritage [3] and wearable MR technology in exhibitions [21], identifying trends and challenges in adopting these technologies. Key insights include the importance of designing user-centered experiences that balance technical complexity with accessibility and relevance to diverse audiences.

Other notable examples include Plecher et al. [14], who explored MR as a tool for cultural heritage storytelling, demonstrating its potential for creating immersive and narrative-driven experiences. Dima et al. [5] investigated MR's use in decolonizing heritage sites, leveraging its ability to present multiple perspectives and engage visitors emotionally and intellectually. Vosinakis et al. [19] employed MR to co-design playful installations, showcasing its versatility in creating both educational and entertaining heritage experiences.

Schönauer et al. [16, 15] introduced the ImmersiveDeck, an XR platform designed for creating informal learning and first responder training experiences. The platform's ability to support multisensory and embodied interactions has implications for cultural heritage applications, particularly in fostering engaging and practical learning environments.

A similarly rich location-based installation embedded in museum settings is "Thresholds" by Tennent et al. [18], which demonstrates how immersive technologies can seamlessly integrate with traditional exhibition spaces. This project includes highlights the potential for VR to enhance visitor engagement by providing contextually rich and interactive storytelling experiences within cultural institutions.

2.2 Tangible Interaction in Cultural Heritage

Tangible interaction has become a key focus in the design of engaging cultural heritage experiences, where physical objects and sensory feedback are leveraged to deepen visitor immersion and connection to the past. Duranti et al. [7] provide a comprehensive survey of tangible and embodied interactions in museums, highlighting the integration of smart objects and replicas that allow visitors to handle physical artifacts while receiving augmented digital content. This approach bridges the gap between the intangible and the physical, fostering an enriched understanding of cultural heritage.

Dima et al. [6] explored haptic augmented reality (AR) as a means to engage museum visitors with historical artifacts, demonstrating how touch-based interactions can significantly enhance the sensory and cognitive dimensions of learning. Similarly, Petrelli et al. [13] introduced a tangible interaction toolkit for designing heritage installations, enabling rapid prototyping of experiences that blend physical objects with interactive technology to create meaningful and contextually relevant visitor engagements. Projects such as Ioannidis et al.'s "We Dare You" [10] have further demonstrated the potential of tactile and substitutional reality systems in museum spaces, where physical replicas and real-world interactions are embedded into immersive virtual environments. These studies underscore the importance of tangible interaction in fostering active participation and a sense of presence among museum-goers.

3 Description of the MR Installation

The MR platform presented in this study combines established XR elements with novel multisensory and collaborative features, aiming to deliver a unique, immersive experience beyond conventional multi-user VR setups. Participants, represented by avatars, freely navigate a shared virtual environment, interact with virtual objects and avatars, and engage in conversations in real-time. Each participant wears an HP Reverb G2 HMD, tethered to a backpack PC for local rendering to minimize latency. The installation is site-specific, with the physical room precisely mapped onto the virtual environment on a 1:1 scale, ensuring that real-world structures align perfectly with their virtual counterparts. To create the virtual environment, a digital twin of the physical room was generated using photogrammetry and Lidar scanning techniques. The resulting 3D model was used both for virtual world development and for placing ceiling markers required for accurate tracking. This alignment enhances the sense of tangibility, spatial awareness, and immersion by enabling users to physically touch walls and interact with architectural features as they explore (Fig. 2).

To achieve this precise real-virtual alignment, the platform employs a combination of off-the-shelf hardware and custom-developed software. A proprietary real-time tracking system ensures accurate synchronization of users' movements and interactions [15]. Unlike traditional VR systems where the virtual world remains entirely detached from the physical space, this setup bridges the two realms, enhancing presence and realism—critical for cultural heritage scenarios that demand high spatial fidelity.

A key distinguishing feature of this platform is its emphasis on multisensory engagement. While visual and auditory stimuli are standard in most XR applications, this installation meaningfully incorporates tactile interaction, addressing a known gap in XR research [20]. Visitors physically interact with real objects integrated into the virtual environment, such as a 3D-printed vase. Such movable physical objects were integrated into the virtual environment using an autonomous object tracking system (Fig. 2). The hypothesis was that these tangible elements, combined with embodied interaction, would deepen visitors' sense of presence and engagement.

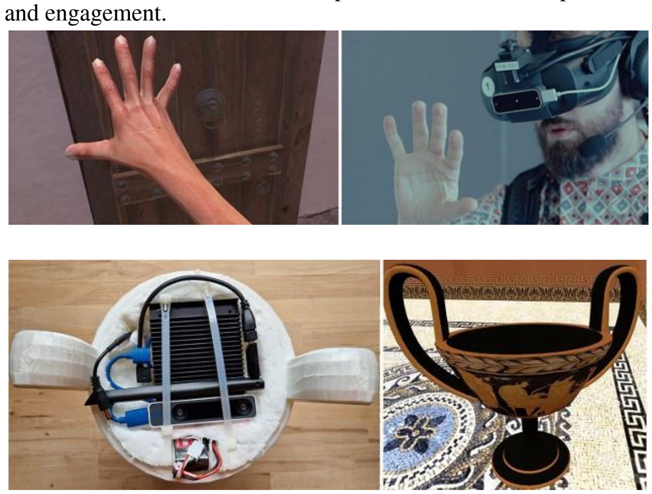

Figure 2: Above: Users' virtual hand (left) and real hand (right) are tracked. Below: The object-tracked 3D printed vase handled by visitors in the MR environment (left) and its virtual counterpart (right).

The MR experience featured a guided storytelling scenario set in Classical Athens, designed to immerse visitors in the daily life of an Athenian family. Participants assumed the roles of guests invited to the home of a middle-class pottery merchant. The group entered a specially constructed physical environment that corresponded to the layout of the virtual house. Guided by virtual hosts, visitors could walk through different rooms of the house, ascend a staircase to the upper level, and gather around the hearth to participate in household activities. These activities included preparing a meal, offering aromatic incense to the gods (which visitors could smell), and interacting with virtual and tangible objects using natural hand gestures (Fig. 3).

Figure 3: Participants in the real space (above) and their avatars in the virtual world (below) interacting in MR.

4 Evaluation

The site-specific nature of the offered experience creates the need for testing on-site and evaluating the site-specific requirements and their impact on the users' overall embodied experience. For this reason, the evaluation of the MR experience employed various methods to cover the whole design continuum, from evaluating the development stages of tools, methodologies, and experiences (formative evaluation) to final prototypes (summative evaluation). To capture the impact of the experience and its multifaceted influence in the informal learning and edutainment context of the cultural institution it was deployed in, the evaluation employed a holistic, triangulated, multimethod, and multilevel approach, covering not only the usability, but also the achievement of pedagogical and experiential goals, meeting the operational, and technical objectives, too [21]. Furthermore, the evaluation framework that was developed considers all the general and typical requirements or risks of a collaborative XR experience to guarantee users' safety and hygiene.

4.1 Methodology

4.1.1 Evaluation Framework

All evaluation activity was broadly guided by six axes established early in the project's lifetime, during the requirements analysis phase (see Table 1). These axes serve as the basis for the development of a cross-context evaluation framework tailored to assess immersive experiences in collaborative room-scale MR environments. The evaluation framework was applied in evaluation studies in two diverse application domains, adding depth and practical relevance to its effectiveness and adaptability. In this paper we present its application in the cultural heritage domain, focusing on the pedagogical (PE) and experiential (EX) aspects of embodiment and tangibility.

Table 1. Design and Evaluation Axes

Axis	Description
General (GE)	Issues that apply to any XR experience, e.g., tackle motion & cybersickness or are related to the equipment specifications.
Site (SI)	Issues regarding the venue and the specifications of the site where the XR is installed.
Pedagogical (PE)	Issues to maximise the effectiveness of informal learning for visitors
Experiential (EX)	Issues that are needed for creating a positive overall experience for visitors, e.g., sense of embodiment and immersion, interactivity, multisensory stimuli.
Technical (TE)	Issues that are related to technical specifications of the XR equipment and experience, e.g., usability, the fidelity of the simulations, etc.
Operational (OP)	Practicalities and issues that are created by physical and organisational limitations and challenges, e.g., staff expertise or shortage, visitor flow.

4.1.2 Participants

An open call was created and sent out via e-mail to our networks of colleagues, friends, and acquaintances, approximately two weeks before the start of the evaluation sessions.

A total of 73 visitors were recruited, forming 19 groups with an average of 4 participants each. We had no influence over the selection and (gender, age, experience) balancing of participants. As visitors were recruited through a semi-open call, it was impossible for us to control who would finally participate. Thus, it happened that female participants outnumbered males. Two participants identified as non-binary.

4.1.3 Procedure

The following procedure was applied to all participants who arrived to the venue to take part in the MR experience: 1) Group formation, 2) Researchers' introduction to the experience and consent, 3) Pre-experience questionnaire, 4) Observation of the groups during their experience, 5) Post-experience questionnaire, 6) Post-experience focus group.

Specifically, participants were asked to complete pre- and post-experience questionnaires. The pre-experience questionnaire (Pre-X) included 10 single and multiple-choice questions and questions using Likert scales. The post-experience (Post-X) questionnaire comprised different sections containing 18 questions (Fig. 4). Most questions were either multiple choice or Likert ranking, while one was open-ended, asking for a free text response. None of the questions were mandatory.

5 Findings

This section presents a selection of the aggregated qualitative data gathered from the Pre-X and Post-X questionnaires, the observation of the users' experience, and the verbal feedback from the focus group interviews. A first level of analysis was conducted by three researchers (R1-R3), summarising patterns across the collected data. As a next step, we are currently analysing these findings to yield insights and guidelines for the design of such MR experiences in cultural contexts.

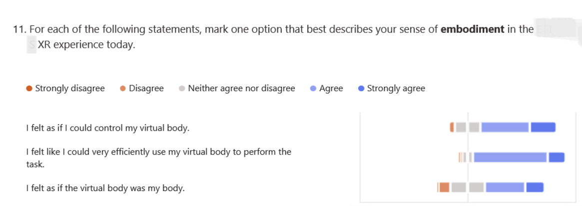

Figure 4: Participants' responses on their sense of embodiment.

Specifically, the observation of participants during their experience was guided by the pre-identified axes. Then, short video snippets were created, grouping the various sections of the MR experience and activities of interest. Finally, all 19 focus group interviews recording visitors' opinions and feelings about the experience were transcribed verbatim by R1 who acted as a moderator and thus could distinguish participants' voices. R2 and R3 incorporated their written notes into the transcribed interviews. This resulted in approximately 120 pages of text. Every transcribed segment was assigned to one or more themes, using a thematic analysis approach [4].

5.1 Room-Scale Movement and Embodiment

5.1.1 Embodiment and Virtual Hands

Participants consistently reported that using their virtual bodies to navigate and perform tasks in the MR environment felt natural and intuitive. Notably, their attention was frequently drawn to their (virtual) hands, which they used extensively during the experience (Fig. 5). Observing their virtual hands, moving them, and using them to interact with objects reinforced their sense of embodiment. Quotes from participants highlight this connection:

"I am excited by the accuracy between my body and the space, both the physical and the virtual one. I had never worn such a headset and equipment" (g1-03, male participant).

"I observed my VR body and my hands. I was moving my hands, I touched objects, and I interacted with the environment. My virtual hands had two moles, and I wondered to whom they belonged. I felt like I was in a parallel universe" (g7-01, male participant).

"I was impressed by the fact that I could coordinate my hand movements in the virtual space with my real hands, even though the virtual hands were a bit ugly. I had the feeling of my hands. We counted, we gave five, and we did a handshake like in the real world. It was really something!" (g1-03, male participant).

Figure 5: Visitors using their (virtual) hands to interact.

5.1.2 Movement and Spatial Alignment

The ability to freely move around the virtual environment enhanced participants' awareness of their physical and virtual bodies. Many noted how the alignment between the physical and virtual spaces contributed to a heightened sense of immersion. Participant reflections include:

"I was impressed by the matching of the real space with the VR space and the fact that we can move around" (g3-01, female participant).

"I liked very much that I could move around the home. It was so real…" (g3-02, female participant).

"Compared to other VR experiences, which are static, this is more immersive because you can walk" (g6-05, female participant).

"The fact that I could walk around was very interesting, and this is different from other computer games…" (g13-04, male participant).

5.1.3 Interaction with Others

Sharing the experience with other participants, represented as avatars, added a social dimension to the experience, reinforcing the sense of immersion and reducing feelings of isolation. Physical interactions, such as sensing others' proximity or being touched, were particularly impactful (Fig. 6). Participants shared their thoughts:

"I felt the other bodies near me, compared to the virtual characters. Being with others helped me feel immersed in the experience. I felt the existence of g12-01 near to me in space—not just seeing her avatar. I couldn't see her real body in the virtual environment, but I sensed her presence" (g12-02, male participant).

"I felt someone touch me when I was in the corridor" (g5-05, female participant).

"When we were walking around, someone could touch you, and you had the sense that you were not alone there. This was amazing…" (g7-01, female participant).

Figure 6: Moving around and interacting with others by touch.

5.2 Tangible Elements

The MR experience employed a multisensory approach designed to motivate and engage participants through stimulation of hearing, sight, touch, and smell. Engaging multiple senses was identified as one of the most positively received aspects of the experience. These findings align with those of Tennent et al. [18], who emphasized that the "devil is in the details" when evaluating a similar room-scale tactile XR experience, suggesting that multisensory details significantly enhance the overall impact.

The tactile dimension, in particular, was a standout feature for many participants. The ability to touch physical objects, interact with the environment, and make physical contact with avatars was a pleasant surprise for most visitors. Participants shared their impressions:

"I liked very much the fact that we could touch each other." (g4-03, male participant).

"I also liked that I could touch Ippias, my virtual son… this was very nice!" (g16-03, female participant).

"I also liked that we could touch other participants and grab things into our hands. This part was the most interesting." (g18-03, female participant).

A particularly compelling element was the inclusion of a 3D-printed tangible object—a vase—within the virtual environment (see Fig. 1). For many participants, this tangible addition was an unexpected and memorable aspect of the experience, as reflected in the following comments:

"I would also like it if there were more tangible objects. The tangible object was a surprise." (g13-02, female participant).

"When I got the vase into my hands, I said, 'Is this real?' I didn't expect it." (g1-03, male participant).

"I wanted to touch everything. I also grasped the vase before the others. I had the desire to feel the whole space." (g4-03, male participant).

However, some participants reported mixed feelings about the tangible vase. For a few, the experience of touching the vase was stressful:

"The tangible vase made me wonder what it was that I touched. It stressed me a bit and surprised me." (g12-01, female participant).

Additionally, technical glitches with the tangible object were noted, such as poor tracking or inconsistent synchronization with virtual interactions. While some found these issues distracting, most felt they did not significantly detract from the overall experience:

"The tangible vase was trembling from the beginning. Probably something did not function properly." (g11-03, male participant).

"When I passed the vase to someone else, her hands seemed to be away, and the vase was hanging in the air. That was weird." (g16-02, female participant).

"The tangible vase was very promising from a technological point of view. However, the bad tracking of hands made it less effective as an experience. Still, it was amazing!" (g11-02, male participant).

"I am not very familiar with VR, so the trembling of the vase did not affect my experience. I don't have high expectations." (g11-04, male participant).

Despite these issues, the integration of multisensory and tangible elements was largely viewed as a strong positive, enriching the immersive nature of the XR experience.

6 Discussion

Embodiment and tangibility in location-specific, multimodal MR experiences remain relatively underexplored in cultural heritage contexts. This study offers a contribution to this area by examining how these elements influence visitor engagement, immersion, and informal learning in such settings. The findings suggest that while embodied and tangible interactions enrich the experience, they also present specific challenges related to storytelling and narrative coherence.

On the positive side, the evaluation revealed that both embodiment and tangibility contributed significantly to the immersive and engaging nature of the MR experience. The sense of embodiment—facilitated by free movement, natural hand-based interactions, and tactile engagement with the environment—created a strong feeling of presence for participants. Visitors actively explored the reconstructed historical setting rather than passively consuming information, making the experience more dynamic and engaging. Tangibility, especially through physical interaction with a 3D-printed object (the tangible vase), was consistently highlighted as one of the most memorable and novel elements. Participants were surprised and delighted by the unexpected physicality of the object, which bridged the gap between the real and virtual worlds, enhancing their overall sense of immersion.

Social interaction, a key aspect of embodiment, also emerged as an important contributor to engagement. The shared experience allowed visitors to interact with one another physically and virtually, fostering collaboration and playful exploration. Many participants found this element highly enjoyable, noting that it added a unique, interactive dimension to their visit. This social component not only enhanced immersion but also encouraged shared reflection and discussion—valuable outcomes for informal learning environments such as museums.

However, this very strength of embodied and tangible interaction posed a significant challenge to the storytelling aspect of the experience. The narrative, which aimed to guide visitors through a coherent plot in the reconstructed historical setting, was often overshadowed by the playful nature of physical and social interactions. Many participants became so absorbed in interacting with the tangible vase, exploring the virtual environment, and engaging with other visitors that they lost track of the plot. This tension between interaction and narrative coherence reflects a known challenge in the design of XR experiences, particularly in cultural contexts where both learning and storytelling are key objectives. While multisensory engagement and social interaction enhance user immersion, they can also distract from following the intended storyline, diluting the impact of the narrative.

Another area for improvement concerns the pacing and structure of the experience. Several participants expressed a desire for more time to explore and reflect on the content, as the fast pace led to a sense of being rushed and reduced opportunities for contemplation. Additionally, while the multisensory design was generally appreciated, some participants found that the abundance of simultaneous activities created sensory overload, making it difficult to focus on key elements of the plot. Participants also expressed a desire for greater agency within the experience, as some felt that their actions did not meaningfully influence the unfolding events. This highlights the need for balancing rich, interactive features with clear narrative progression and moments of reflection to enhance both engagement and learning outcomes.

Despite these challenges, the findings underline the educational potential of embodied and tangible MR experiences in cultural contexts. Visitors reported acquiring new factual knowledge and engaging deeply with the reconstructed environment. Notably, the sense of embodiment enabled a hands-on approach to learning, making cultural content more accessible and relatable. Moreover, the experience fostered historical empathy, particularly in scenarios that explored interpersonal relationships in antiquity, helping participants form emotional connections with the past.

Future efforts in designing MR experiences for cultural heritage should focus on resolving the tension between interaction and narrative coherence. One potential approach is to integrate moments of guided reflection or structured narrative breaks to help participants process their experience without disrupting the flow of interaction. Additionally, improving the reliability of tangible elements, such as addressing tracking glitches, could further enhance user engagement without detracting from the plot. By carefully balancing embodiment, tangibility, and storytelling, future MR applications can create more cohesive and impactful experiences that blend learning, play, and narrative in meaningful ways.

7 Conclusion

The findings of this evaluation carry implications for the design and evaluation of XR technology and experiences across various contexts. Moving forward, our aim is to further refine and expand our analysis to yield deeper insights and ultimately propose comprehensive guidelines for designing MR experiences employing tangible and embodied aspects in diverse settings. These guidelines will serve the broader XR community by offering considerations related to operational efficiency, site-specific implementation across different contexts, technical enhancements, experiential qualities, and pedagogical effectiveness. By providing guidance on these crucial layers of XR experiences, we hope to contribute to the continuous improvement of processes and the creation of more impactful and engaging XR encounters.

Figure Credits

All figures have been created as part of the evaluation of the project. Individuals pictured have provided their consent.

Acknowledgments

The authors wish to thank all partners of the project. This work was supported in part by a grant from [Anonymized].

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