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TLIC PAPER

Artificial Intelligence and Extended Reality for Interactive Museum Experiences: Designing Participatory, Multisensory, and Adaptive Spaces for Knowledge Sharing

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ABSTRACT

Museums, archives, and cultural institutions are experiencing a profound transformation, shifting from repositories of exclusive knowledge to interactive and inclusive environments that foster lifelong learning and cultural participation. Building on the historical evolution of collections—from ancient archives and Renaissance *Wunderkammern* to modern public museums—this paper explores how extended reality (XR), AI-driven avatars, and digital storytelling are reshaping the visitor experience. We analyze how immersive projections, conversational agents, and hybrid "phygital" installations developed by e-REAL Labs have enhanced accessibility, engagement, and preservation across projects in Italy, Switzerland, France, and beyond. These solutions demonstrate how static exhibitions can be converted into dynamic experiences where visitors actively co-construct meaning. Drawing on recent design research, we highlight the importance of cognitive ergonomics, memory, and attention management in XR environments, ensuring that technology supports rather than overwhelms perception. The integration of calm and slow technologies provides balance, making digital tools discreet companions to narrative and curatorial intent. Similarly, modular and adaptive design principles allow installations to fit within diverse architectural and cultural contexts without fragmenting visitor experience. Particular focus is placed on the educational dimension of interactive museums., where extended reality (XR) and artificial intelligence (AI) extend learning beyond traditional didactics, This approach engages visitors through multisensory experiences that blend physical artifacts with virtual reconstructions. Multilingual avatars and inclusive design guidelines support accessibility for diverse audiences, including individuals with disabilities and marginalized communities. Ultimately, this paper positions interactive museum experiences as a new paradigm of cultural engagement, where digital transformation does not replace authenticity but enhances it. By merging historical preservation with generative AI and immersive storytelling, museums can transcend physical and cognitive barriers, offering equitable access to cultural heritage and fostering dialogue across generations and cultures.

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KEYWORDS
Interactive museums, extended reality, AI-driven avatars, cognitive ergonomics, inclusive cultural heritage

1 INTRODUCTION

In recent decades, museums, cultural sites, and archives have undergone a radical redefinition, evolving from repositories of exclusive knowledge to interactive, participatory, and inclusive environments that foster cultural accessibility and lifelong learning [1–9]. This transition reflects a broader social and institutional shift: cultural heritage is no longer perceived merely as a collection of preserved objects but as a dynamic ecosystem of narratives, dialogues, and experiences.

At e-REAL Labs, our work has focused on this transformation, integrating extended reality (XR), generative artificial intelligence (AI), and interactive storytelling into the design of cultural spaces. Through collaborations with leading museums and research centers, including the Regional Museum of Natural Sciences in Turin, UNESCO in Paris, and cross-border projects such as *Digit Alps*, we have demonstrated how static exhibitions can be reimagined into immersive journeys that combine physical artifacts with digital reconstructions [10, 27, 55–63]. These solutions not only enhance visitor engagement but also ensure accessibility through multilingual avatars, multisensory installations, and adaptive learning pathways.

The historical roots of museums as places of knowledge—beginning with the Greek *mouseion* and *archeion*, Roman *tabularium*, and Renaissance *Wunderkammern*—illustrate how access to collections was once restricted to elites [11–23]. Over time, particularly during the Enlightenment and the French Revolution, cultural heritage became recognized as a public good, culminating in the modern definition of museums and archives as institutions dedicated to education, transparency, and collective memory [24–31]. Today, this trajectory converges with the opportunities offered by digital technologies, which extend the reach of cultural institutions far beyond physical boundaries.

The integration of XR and AI addresses several pressing challenges faced by contemporary museums:

- ***Engagement and learning*** – immersive storytelling fosters active participation and deeper cognitive connections with heritage [32–34];
- ***Accessibility and inclusion*** – digital tools reduce linguistic, sensory, and cognitive barriers, aligning with international guidelines on universal design [33, 42];
- ***Preservation and innovation*** – digitization and virtual reconstructions safeguard fragile collections while expanding opportunities for study and enjoyment [35–40].

Recent research emphasizes that designing interactive museum environments requires attention not only to technological innovation but also to cognitive ergonomics—managing perception, attention, and memory to avoid overload [33]. Zannoni's work on perception, based on theories from Norman, Kahneman, Broadbent, and Treisman, reminds us that the visitor's capacity to process stimuli is limited, requiring careful modulation of interaction intensity. Similarly, Dall'Osso's studies highlight the importance of modular, adaptive design that respects existing

architectural and cultural contexts, ensuring that XR and AI solutions integrate harmoniously into museums rather than dominating them [65].

Furthermore, the adoption of calm and slow technologies provides balance, enabling digital media to remain discreet, supportive companions rather than intrusive spectacles [43–54]. This aligns with Merleau-Ponty's phenomenological insight into the *primacy of perception*, where lived experience and embodied interaction define meaning [41]. By combining immersive projections, conversational avatars, and natural interaction design, museums can create environments where visitors cease to be passive observers and instead become co-creators of knowledge and cultural memory [55–64].

In this perspective, interactive museum experiences represent not just technological innovation but a paradigm shift in cultural communication. They reconcile historical authenticity with digital transformation, opening new spaces for dialogue across generations and cultures, and ensuring that museums remain at the forefront of education, inclusion, and collective imagination [65]. This approach has been concretely implemented in projects such as the interactive installations at the Regional Museum of Natural Sciences in Turin, where AI-driven avatars and immersive projections transform natural history into participatory learning; the "Mortar Mixer" initiative in Switzerland, which digitally reconstructs medieval building techniques through XR and multilingual generative AI; and the Digital Alpine Museum (DAM), which connects institutions across Italy and France through customizable virtual exhibition halls. Together, these projects—summarized in Figure 1—demonstrate how extended reality and AI can bridge the gap between preservation and innovation, turning static collections into dynamic and inclusive cultural ecosystems.

Project	Key Features	Impact & Achievements
Museum of Natural Sciences, Turin	- **Interactive 3D and AI-Driven Guides**: Historical avatars (Alfred Wallace, Michele Lessona) with dynamic dialogues. - **Immersive Ecosystem Displays**: 18x6m curved projections with augmented reality. - **Cross-Platform Accessibility**: Web, mobile, and interactive kiosks for inclusivity.	- **40% increase** in visitor satisfaction (survey results). - **30% increase** in engagement time per exhibit.
"Mortar" Project, Switzerland	- **3D Reconstruction of Medieval Techniques**: Virtual simulation of mortar mixing. - **AI-Powered Avatars**: Multilingual guides (Italian, German, English) explaining medieval architecture. - **Phygital Integration**: Augmented reality with physical tools and digital replicas.	- Enhanced **understanding of ancient construction** through hands-on & virtual activities. - **Expanded audience reach** via immersive storytelling.
DAM Project: Cross-Border Collaboration (Italy-France ALCOTRA Initiative, ongoing)	- **Virtual Exhibition Halls**: AI-powered avatars guiding thematic journeys. - **3D Modeling of Artifacts**: Digital high-resolution replicas available online and in VR. - **Dynamic Personalization**: Tailored educational experiences.	- **100+ artifacts** to be digitized and accessible. - **Unified cross-border access** to cultural heritage. - **Expected 50% audience increase** through hybrid, multilingual engagement.

Fig. 1. This scheme summarizes three projects that use extended reality, AI, and digitalization to enhance cultural heritage accessibility and engagement. It highlights key features, technological innovations, and measurable impacts on visitor interaction and learning

2 MOUSEION AND ARCHEION: PRIVATE PLACES DEDICATED TO THE MUSES

The origins of museums and archives are deeply rooted in the ancient world, where spaces dedicated to knowledge were closely tied to power, religion, and social hierarchy. The Greek term μουσεῖον (mouseion) indicated a sanctuary of the Muses, deities protecting the arts and sciences. The most celebrated example was the Mouseion of Alexandria, which combined a vast library with facilities for research and philosophical inquiry. Yet, despite its grandeur, this was not a public institution: it was reserved for a small elite of scholars, reinforcing the exclusivity of knowledge in antiquity [11–13].

Alongside the mouseion, the ἀρχεῖον (archeion) served as the official seat of authority where records and administrative documents were preserved. Its primary function was not education but governance, ensuring the continuity of political and legal power. Similarly, the μητρῷον (metroon) in Athens—originally a temple to maternal deities such as Rhea or Cybele—became the central public archive of the polis, symbolically blending sacredness with state administration [14–16]. These spaces highlight a recurring theme: access to recorded knowledge was mediated by authority, whether divine or civic, and strictly regulated.

The Roman world continued this tradition. The Tabularium, located in the heart of ancient Rome, was dedicated to storing state documents, laws, and decrees. Like its Greek predecessors, it functioned primarily as an administrative tool rather than a cultural or educational space. These repositories underscored the principle that knowledge equaled power, with archives acting as instruments of governance rather than as public resources [17–19].

In parallel, other institutions such as the bibliotheca in Roman times or the medieval scriptorium, armarium, sanctuarium, and thesaurus reinforced the restricted nature of access to written and sacred materials. Monastic scriptoria became the custodians of knowledge during the Middle Ages, yet accessibility remained confined to monks and, occasionally, selected scholars. Collections of relics, liturgical objects, and sacred texts were housed in protected environments where the sanctity of space mirrored the sanctity of knowledge [20–22].

The common denominator across these institutions—whether Greek, Roman, or medieval—was the principle of limited access. Knowledge was considered a privilege bestowed upon certain groups: priests, officials, or scholars. Its preservation served not only intellectual purposes but also the consolidation of hierarchical and political structures. Archives and proto-museums were not neutral spaces; rather, they actively contributed to producing and legitimizing social order, reinforcing the distance between the elite and the wider population [23].

In sum, the archaeology of knowledge reveals that the earliest forms of museums and archives were neither inclusive nor participatory. Instead, they were instruments of control, exclusivity, and power—antecedents that stand in stark contrast to today's aspiration to design museums as open, dialogic, and universally accessible environments.

3 THE RENAISSANCE AND THE BIRTH OF MUSEUMS: PRIVATE PLACES FOR INTERDISCIPLINARY DIALOGUE

During the late Middle Ages, collections of objects were primarily associated with religious institutions and noble courts. Cathedrals safeguarded relics and liturgical

treasures, while monasteries preserved manuscripts in their libraries and scriptoria. These were not yet museums in the modern sense but rather instruments of spiritual and political legitimization, accessible to a very restricted elite [24].

With the rise of Humanism in the 14th and 15th centuries, a gradual shift occurred: the focus of collecting moved from religious devotion to intellectual curiosity. Renaissance courts in Italy became vibrant cultural hubs where princes and scholars assembled manuscripts, natural specimens, artworks, and antiquities. These collections reflected the humanistic ideal of harmony among art, nature, and knowledge, embodying the interdisciplinary dialogue that characterized Renaissance thought [25–26].

A striking example of this transformation was the emergence of the studiolo—small, intimate spaces for contemplation and collection, such as Federico da Montefeltro's studiolo in Urbino. These environments anticipated the modern museum by integrating scholarship, aesthetics, and symbolic representation. They were places where rulers staged their erudition and power, while simultaneously nurturing intellectual exploration.

Equally influential were the Wunderkammern or cabinets of curiosities, which flourished in Renaissance Europe. These spaces brought together natural objects, scientific instruments, exotic artifacts, and works of art, often displayed without rigid taxonomies. Their eclecticism reflected the epistemological framework of the time, when classification was less important than evoking wonder and stimulating dialogue among disciplines. Although these collections remained largely private, they laid the groundwork for the encyclopedic vision of modern museums [27].

Among the most famous examples were the Medici collections in Florence, which eventually gave rise to the Uffizi Gallery, and the princely collections in Vienna, Dresden, and Prague. These assemblages not only elevated the prestige of their owners but also foreshadowed the future transition from private collecting to public museums, a process that unfolded from the 17th to the 19th centuries.

Archives also underwent significant evolution in this period. With the rise of centralized monarchies and city-states, archives became crucial for the administration of justice, taxation, and diplomacy. A landmark was the General Archive of Simancas in Spain (1540), often considered the first modern state archive. Its establishment symbolized the growing recognition of archives as essential tools for governance, transparency, and the preservation of collective memory [28–29].

Taken together, the Renaissance innovations in collecting and archiving redefined the relationship between knowledge, power, and representation. Museums and archives began to emerge not merely as instruments of control but as spaces of interdisciplinary inquiry, where art, science, and politics intersected. Although still far from universal accessibility, these institutions embodied the intellectual ferment of the Renaissance and prepared the ground for the Enlightenment ideal of cultural heritage as a public good.

4 MUSEUMS AND ARCHIVES AS PUBLIC GOODS: CULTURAL HERITAGE AND LIFELONG EDUCATION

Until the 18th century, museums and archives—whether ecclesiastical treasuries, monastic libraries, or princely collections—were still largely private institutions, accessible only to clergy, scholars, or members of the elite. Yet even in antiquity, Roman law had already recognized that certain cultural and documentary assets, such as the imperial collections or the tabularia, were to be considered property of the state, symbolically linked to the collective identity of the community [25–26].

A decisive shift occurred during the Enlightenment, when knowledge and cultural heritage came to be seen as a universal right rather than a privilege for the few. The French Revolution played a crucial role in this transformation: in 1793, the Louvre was opened as a public museum, converting the royal collections into national heritage at the service of citizens. At the same time, ecclesiastical and aristocratic archives were seized and centralized, ensuring that historical and administrative records could be accessed in the name of transparency and accountability [27–28].

Throughout the 19th century, the public nature of cultural heritage became progressively institutionalized through laws and civil codifications. The Napoleonic Code (1804) introduced specific provisions for the management of public assets, including cultural goods. Such legislation not only defined rules for conservation and accessibility but also emphasized their educational purpose, binding the legitimacy of political institutions to the protection and promotion of cultural heritage [29].

The 20th century reinforced this trend. Modern constitutions, such as the Italian Constitution of 1948, explicitly recognized culture as both a right and a duty of the state, affirming that heritage must be safeguarded and enhanced for the benefit of society as a whole. Parallel to national frameworks, international organizations such as UNESCO and the International Council of Museums (ICOM) articulated shared definitions of museums as public institutions serving society. Their mission expanded beyond preservation to include education, inclusivity, and lifelong learning, establishing museums as sites of general interest that foster both individual growth and collective identity [30–31].

This transformation had profound implications. By framing cultural heritage as a public good, societies shifted the perception of museums and archives from static repositories into dynamic institutions of civic engagement. They became places where history, memory, and creativity intersected, nurturing not only knowledge acquisition but also democratic participation. The idea of accessibility was no longer limited to physical entry into spaces but extended to the broader principle of universal cultural participation, laying the groundwork for the digital and interactive transformations of the present.

5 MUSEUMS, CULTURAL SITES, AND ARCHIVES AS INCLUSIVE EDUCATIONAL SPACES

Today, museums, cultural sites, and archives are increasingly recognized as collective assets whose value extends beyond preservation to include their ability to promote universal accessibility, inclusion, and active participation. These institutions are no longer conceived solely as spaces for contemplation or consultation; they have become platforms for dialogue and engagement, capable of connecting people, cultures, and generations [32].

In this context, accessibility has expanded from its initial meaning—guaranteeing physical entry—into a much broader concept. It now encompasses cognitive accessibility (designing exhibitions that avoid information overload and facilitate comprehension), linguistic accessibility (multilingual interfaces and adaptive storytelling), and social accessibility (welcoming marginalized groups, families, and individuals with disabilities). This evolution responds to the growing awareness that cultural heritage must serve the diverse needs of contemporary societies rather than reinforcing elitist exclusions.

Digital transformation has been a powerful driver of this process. Digitization of collections, immersive projections, and online platforms now enable institutions to extend their reach beyond physical boundaries. Visitors can explore hidden storage areas through virtual tours, interact with reconstructions of lost or fragile artifacts, and

participate in phygital exhibitions that blend physical and digital dimensions. These tools make it possible to reduce barriers of distance, language, and ability, ensuring that collections are accessible to audiences who would otherwise be excluded.

At the same time, inclusive design frameworks have become essential. At e-REAL Labs, in collaboration with the University of Bologna, we have tested and implemented standards and guidelines for interactive museum design, ensuring that installations respect the principles of usability, equity, and participation. These include not only compliance with international standards (such as WCAG 2.1 for web accessibility) but also design heuristics based on experiential and cognitive psychology. The objective is to create environments where visitors are not overwhelmed but can actively co-construct meaning.

This participatory vision also aligns with the educational role of museums. As highlighted in recent scholarship, museums increasingly act as learning ecosystems, fostering critical thinking, creativity, and intercultural understanding. By providing immersive storytelling and adaptive learning paths, they encourage visitors to move beyond passive observation toward active engagement and co-creation of knowledge. In this way, museums support not only lifelong learning but also the cultivation of citizenship and democratic values.

In sum, by embracing inclusivity, accessibility, and interactivity, museums, cultural sites, and archives are redefining their role in society. They have become laboratories of participation, where cultural heritage is not merely preserved but actively reinterpreted, connecting past traditions with present challenges and future aspirations [32].

6 DESIGNING INCLUSIVE AND PARTICIPATORY EDUCATIONAL SPACES

Museums, cultural sites, and archives can be understood today as gateways to unexplored worlds and bridges between eras and cultures, where visitors are invited not only to observe but also to participate in the creation of meaning. The contemporary challenge is to design spaces that foster dialogue, immersion, and co-experience, thereby transforming visitors from passive spectators into active participants [33].

The 2022 ICOM definition of museums emphasizes their dual role as institutions of preservation and education, while explicitly recognizing their social mission and their contribution to well-being and lifelong learning. Many institutions are now embracing edutainment approaches, combining traditional scholarship with interactive and playful elements. Exhibitions increasingly adopt phygital and hybrid models, in which the physical environment is enhanced by digital overlays, extending the reach of narratives and allowing multiple forms of engagement [33].

Yet these innovations are not without challenges. Technical integration often encounters malfunctions, uneven accessibility, or incompatibility with existing exhibition layouts. Visitors may also face cognitive overload when multimedia content is excessive or poorly structured, leading to reduced comprehension and engagement. Moreover, overly individualized digital pathways can undermine opportunities for shared interpretation and collective discussion, which remain essential dimensions of cultural experience [33].

To address these issues, the design of interactive museum environments must carefully balance tradition and innovation. On one hand, the authenticity of artifacts and the integrity of curatorial narratives must be preserved. On the other, digital technologies should be deployed to enhance rather than overshadow these elements. Research in cognitive psychology and human–computer interaction highlights the need to consider perceptual limits, memory constraints, and attentional dynamics

when creating XR-based experiences. Zannoni, drawing on the work of Norman, Kahneman, and Treisman, has shown that interactive environments must respect the finite capacity of human attention, ensuring that interaction stimulates curiosity without saturating cognitive resources [33].

Another key principle is participatory design. Co-creation with visitors and institutional stakeholders ensures that technological installations align with cultural objectives, spatial conditions, and audience expectations. Dall'Osso's studies on adaptive museum design stress the importance of modularity and context-sensitivity: technologies should integrate seamlessly into pre-existing spaces, maintaining architectural harmony and cultural coherence [33].

Ultimately, the goal of designing inclusive and participatory spaces is not to create technological spectacles but to establish learning environments that are emotionally resonant, cognitively sustainable, and socially inclusive. In these environments, visitors can engage in dialogue with collections, curators, and one another, strengthening cultural identity and collective memory. By combining immersive storytelling with accessibility standards and participatory methodologies, museums and archives can redefine themselves as open laboratories of cultural democracy, where heritage is preserved, interpreted, and continuously reinvented [33].

7 EXTENDED REALITY AND THE METAVERSE

In recent years, extended reality (XR) technologies—including augmented reality (AR), virtual reality (VR), and mixed reality (MR)—have profoundly reshaped the ways in which museums, cultural sites, and archives design visitor experiences. These tools enable multisensory immersion, allowing audiences to explore reconstructed environments, interact with 3D objects, and engage in narratives that transcend the physical limits of collections [34–35].

Several pioneering institutions have embraced XR to expand both educational and curatorial possibilities. Through AR applications, visitors can visualize lost architectural features directly over ruins; VR headsets allow them to walk inside faithfully reconstructed heritage sites; and MR solutions integrate digital content into real artifacts, producing layered experiences of interpretation. These practices not only enrich learning but also create new modes of cultural storytelling, fostering emotional connections that enhance memory and retention [36].

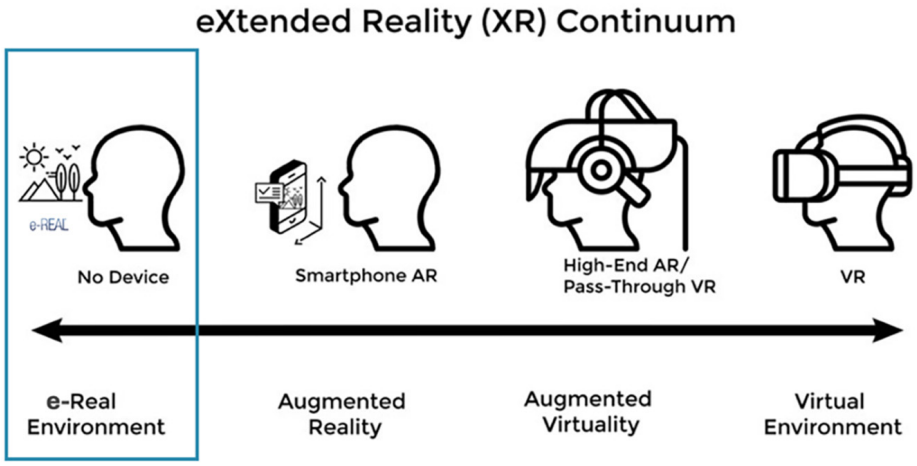

Fig. 2. The extended reality (XR) continuum and the uniqueness of e-REAL solutions, which usually do not require devices or wearable augments, make them easy to use and manage

The emergence of the metaverse has further expanded the horizon. Conceived as an interoperable and persistent digital environment, the metaverse offers museums the possibility of building virtual exhibition halls, accessible globally, where audiences can interact with avatars, curators, and each other in real time. Projects such as digital twins of entire collections or collaborative cultural hubs demonstrate the potential to overcome geographic and logistical barriers, making cultural heritage universally accessible [37].

However, these opportunities come with challenges. The absence of common interoperability standards risks fragmenting experiences across platforms, limiting scalability and long-term sustainability. There are also risks of cognitive overload, especially when XR environments present excessive stimuli without ergonomic design, leading to reduced comprehension rather than enhanced learning. Furthermore, the persistence of the digital divide—in terms of access to high-speed internet, devices, and digital literacy—may exacerbate inequalities rather than reduce them [38–39].

To address these risks, scholars and designers emphasize the adoption of calm and slow technologies, which remain discreetly in the background and allow visitors to control the pace of interaction. XR should not become an intrusive spectacle but a supportive medium, reinforcing curatorial intent and facilitating reflection [33, 40]. Likewise, ethical principles regarding data privacy, accessibility, and inclusivity must guide the implementation of metaverse projects, ensuring that these environments are open, transparent, and aligned with the social mission of museums.

Ultimately, XR and the metaverse should be understood not as ends in themselves but as pedagogical and cultural tools. When thoughtfully integrated, they enable museums and archives to transform into phygital ecosystems, where the physical and digital coexist in harmony. Such environments foster both individual exploration and collective participation, offering new ways to experience heritage while respecting its authenticity and complexity [34–40].

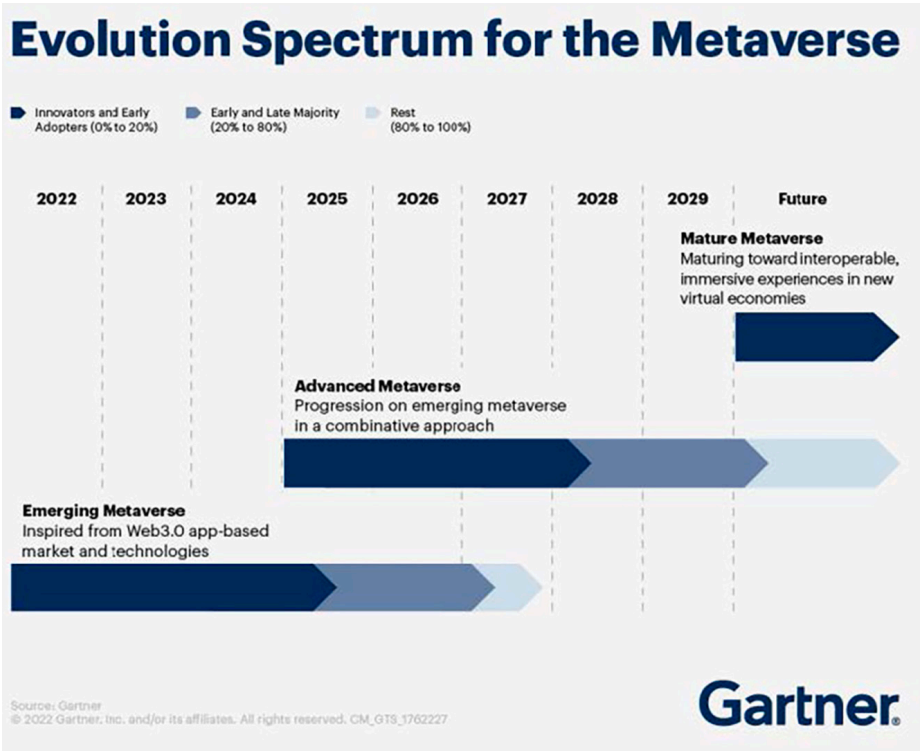

Fig. 3. The next evolution of the metaverse according to Gartner Group projections

8 DESIGNING INTERACTIVE MUSEUM EXPERIENCES

Designing interactive museum environments requires balancing technological innovation with human-centered principles, ensuring that immersive tools enhance rather than overwhelm cultural meaning. The phenomenological tradition reminds us that perception is primary: as Merleau-Ponty argued, our embodied interaction with the world is the foundation of experience. This insight underscores the need to design exhibitions where visitors remain agents of interpretation, rather than passive recipients of digital stimuli [41].

Recent design research highlights several core principles for interactive cultural spaces. First, technologies should be transparent and unobtrusive, in line with the concepts of *calm* and *slow technologies*. Instead of competing for attention, XR and AI tools should remain discreet companions, surfacing only when they enrich storytelling or facilitate accessibility [42]. This approach prevents cognitive overload and preserves the contemplative dimension of cultural encounters.

Second, interactive design must consider cognitive ergonomics: memory, attention, and perception operate within limits. Zannoni's reflections, grounded in the work of Norman, Kahneman, Broadbent, and Treisman, show that exhibitions risk becoming ineffective when information exceeds these thresholds. Proper pacing, multisensory balance, and adaptive interfaces help ensure that engagement fosters deep learning rather than superficial distraction [33, 42].

Third, modularity and adaptability are crucial. As Dall'Osso argues, installations should integrate seamlessly into pre-existing spaces, respecting their architectural and symbolic identities while allowing flexibility for future updates [42]. This perspective supports sustainable design, reducing costs and enabling institutions to evolve without abandoning their heritage.

Fourth, inclusivity must remain a central goal. International guidelines stress the importance of universal design, ensuring that visitors of all ages, abilities, and cultural backgrounds can fully participate. Multilingual conversational avatars, multisensory installations, and customizable learning paths are concrete strategies for creating equitable experiences that align with the ICOM definition of museums as institutions serving society in its entirety [43].

Finally, the design of interactive museum experiences should be guided by participatory methodologies. Involving curators, educators, local communities, and visitors in the co-design process ensures that digital solutions are not imposed from outside but emerge from dialogue with cultural contexts and institutional missions. This participatory ethos transforms museums into living laboratories of cultural democracy, where heritage is continually reinterpreted in light of contemporary challenges [44].

In sum, designing interactive museum experiences means crafting environments where technology supports narrative, cognition, and inclusion. By grounding design in phenomenology, cognitive science, and participatory practice, museums can embrace innovation while remaining faithful to their cultural and educational mission [41–44].

9 EXAMPLES OF INTERACTIVE AND IMMERSIVE MUSEUM PROJECTS

The application of XR, AI, and interactive storytelling in museums has already generated a diverse portfolio of projects that illustrate both the opportunities and challenges of digital transformation. These initiatives demonstrate how immersive

environments can transform visitor engagement, foster accessibility, and enhance the educational mission of cultural institutions [45–46].

One significant example is the Digital Alpine Museum (DAM), a cross-border initiative connecting Italian and French institutions through a network of virtual exhibition halls. DAM enables visitors to explore cultural and natural heritage beyond national boundaries, offering customizable phygital experiences that integrate physical displays with virtual reconstructions. The project underscores how digital museums can serve as cultural bridges, promoting both local identity and international dialogue [47].

Similarly, at the Regional Museum of Natural Sciences in Turin, immersive projections and conversational avatars have been employed to create narrative-driven installations. Visitors engage in dialogues with AI-powered agents that explain natural history, encourage inquiry, and adapt their responses to different age groups and languages. This approach combines scientific rigor with playful edutainment, demonstrating how museums can support both formal and informal learning [48].

In Switzerland, the "Mortar Mixer" project showcases how XR can reconstruct traditional building techniques, allowing users to virtually experience medieval craftsmanship. By merging tangible artifacts with digital simulations, the project fosters a multisensory understanding of heritage that would otherwise be inaccessible to contemporary audiences. Its modular design also illustrates the potential for scalability and adaptation to diverse cultural contexts [49].

Other noteworthy experiments include the integration of projection mapping in historical sites such as castles, cathedrals, and archaeological areas. By animating walls, ceilings, and artifacts, projection mapping can revitalize spaces without physically altering them, offering visitors immersive narratives while preserving the authenticity of cultural assets. These installations align with the principles of calm technologies, ensuring that digital interventions remain reversible and respectful of heritage [50–51].

Internationally, collaborations with organizations such as UNESCO and Harvard University have supported projects that use XR and AI for both cultural dissemination and research. For example, UNESCO initiatives have leveraged digital archives and virtual reconstructions to safeguard endangered heritage, while university-led projects have developed XR platforms for cross-cultural learning and simulation-based education [52–53].

Finally, several initiatives emphasize participatory co-creation, inviting communities to contribute content, stories, and perspectives to digital exhibits. These projects highlight the potential of museums to become open platforms for collective memory, where technology amplifies the voices of diverse stakeholders rather than imposing a single narrative [54].

Taken together, these examples illustrate the richness of possibilities offered by XR and AI in the cultural sector. They confirm that when thoughtfully designed, immersive projects can enhance accessibility, strengthen cultural identity, and support the mission of museums as inclusive spaces of lifelong learning [45–54].

10 THE ROLE OF E-REAL LABS IN DESIGNING INTERACTIVE AND INCLUSIVE EXPERIENCES

The projects developed by e-REAL Labs over the past decade provide a concrete demonstration of how AI, XR, and interactive storytelling can transform museums, cultural sites, and archives into inclusive, adaptive, and participatory spaces.

Rooted in a philosophy that integrates cognitive ergonomics, educational design, and technological innovation, e-REAL's approach has been tested in numerous cultural contexts, both in Italy and internationally [55–56].

A flagship initiative has been the collaboration with the Regional Museum of Natural Sciences in Turin, where immersive projections, interactive holographic displays, and multilingual avatars were implemented to transform traditional exhibits into multisensory learning environments. These installations allow visitors to engage in simulated dialogues with AI-driven agents, providing explanations, answering questions, and adapting communication to different audiences. By blending scientific accuracy with edutainment strategies, the museum has succeeded in attracting both specialized audiences and families [57].

Internationally, e-REAL Labs contributed to the Digital Alpine Museum (DAM), which connects institutions across Italy and France. DAM leverages XR and cloud-based infrastructures to create shared virtual exhibition spaces, allowing visitors to explore cultural heritage beyond physical borders. Through customizable scenarios and interactive storytelling, DAM exemplifies how phygital ecosystems can support cross-cultural learning and foster international collaboration [58].

In Switzerland, the "Mortar Mixer" project illustrates how e-REAL integrates historical reconstruction with immersive learning. By combining physical artifacts with XR simulations of medieval construction techniques, the project enables users to experience heritage through embodied interaction. This aligns with Dall'Osso's design principles on modularity and adaptability, ensuring that installations respect the architectural and cultural context while remaining scalable [59].

Beyond specific projects, e-REAL has developed a methodological framework based on the Responsible Technology Principles, ensuring that innovation is always aligned with inclusivity, accessibility, and sustainability. This includes:

- **Human-centered immersion**, privileging intuitive interfaces and adaptive storytelling;
- **Inclusive accessibility**, with solutions compliant with WCAG and EN standards, and avatars available in multiple languages;
- **Ethical AI**, which ensures transparency, privacy, and explainability of algorithms;
- **Cultural adaptability**, allowing scenarios to be tailored to diverse social and linguistic contexts [60–61].

Furthermore, e-REAL's emphasis on participatory co-design ensures that projects are developed collaboratively with curators, educators, and communities. This participatory ethos not only increases institutional ownership but also guarantees that interactive solutions remain culturally resonant and pedagogically meaningful [62–63].

Taken together, these experiences position e-REAL Labs as a reference point for innovation in the cultural sector, demonstrating how digital transformation can reconcile the preservation of authenticity with the demand for accessibility and engagement. By bridging past and future, e-REAL enables museums to become living laboratories of cultural democracy, where heritage is safeguarded, interpreted, and continuously reinvented.

Fig. 4. Interactive projection mapping and conversational agents (avatars or digital humans: Alfred Wallace and Michele Lessona) equipped with generative artificial intelligence capable of responding to visitor questions, created for the Museum of Natural Sciences in Turin

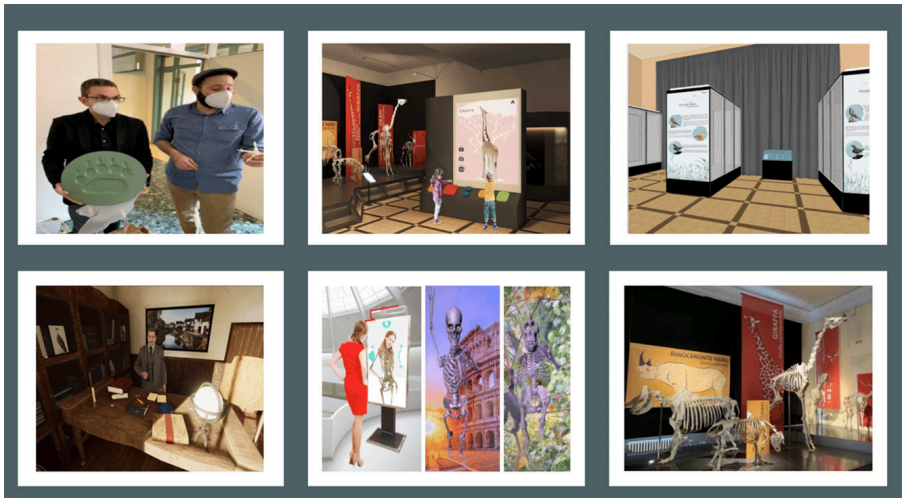

Fig. 5. 3D prints for tactile exploration, interactive projections of animals, animal sounds available even outside the museum, an avatar of Ettore Arrigoni that tracks visitor questions, and augmented reality totems for exploring evolution and comparing human and chimpanzee skeletons (installations created for the Civic Museum of Zoology in Rome)

Fig. 6. Examples of immersive and interactive experiences created for the Italian Embassy in the USA, Washington DC, the School of Design at the Politecnico di Milano, Italy, the Università della Svizzera Italiana in Lugano, Switzerland, and UNESCO, Paris

Fig. 7. Examples of immersive and interactive projections developed for the Regional Museum of Natural Sciences in Turin, Italy

Fig. 8. 3D reconstruction of a medieval mortar mixer for lime mortar, operable virtually both in an exhibition space and online. This installation was created in collaboration with the Università della Svizzera Italiana (USI) in Lugano and the Scuola Professionale della Svizzera Italiana (SUPSI) in Manno, UNESCO, Paris (France), and the San Giovanni Foundation (Kloster St. Johann) in Müstair, on behalf of the Swiss Confederation and the city of Bellinzona, Switzerland

Fig. 9. Examples of embodied conversational agents (avatars or digital humans) developed for the Harvard Center for Medical Simulation in Boston, Northwestern University in Chicago, and George Washington University in Washington, DC

Fig. 10. Other embodied conversational agents (avatars or digital humans) developed for the Museum of Zoology in Rome, Italy, the Regional Museum of Natural Sciences in Turin, Italy, the Virtual Museum of the Digit Alps cross-border project, which involves the Regions Aoste Valley and Liguria in Italy and the Departments of Savoy and the High Alps in France

11 CONCLUSIONS

The evolution of museums, cultural sites, and archives—from the exclusive spaces of antiquity to today's inclusive and participatory institutions—illustrates a long trajectory of transformation in the relationship between knowledge, power, and society. In the 21st century, this trajectory converges with the opportunities offered by extended reality (XR), artificial intelligence (AI), and immersive storytelling, which enable cultural heritage to transcend physical, linguistic, and cognitive barriers [64].

The projects analyzed in this paper confirm that interactive museum experiences are not simply technological add-ons but represent a paradigm shift in cultural communication. By combining authenticity with innovation, they allow institutions to design spaces where visitors are co-creators of meaning, actively engaging with collections, narratives, and communities. This participatory approach aligns with international frameworks such as the ICOM definition of museums, which emphasizes their social mission and contribution to education, inclusion, and well-being [65].

Key lessons emerge from the case studies:

- **Immersive design** fosters deeper cognitive and emotional connections with heritage, enhancing memory and learning outcomes.
- **Inclusive accessibility** ensures that digital transformations extend participation rather than reproduce exclusions, addressing linguistic, sensory, and social barriers.

- **Responsible AI and XR**—guided by principles of transparency, data ethics, and cultural sensitivity—are essential to safeguard trust and authenticity.
- **Participatory co-design** with curators, educators, and communities strengthens institutional ownership and ensures relevance.

Looking forward, museums and cultural institutions face both challenges and opportunities. Issues of digital divide, interoperability, and sustainability must be addressed to ensure that XR and AI solutions remain equitable and durable. At the same time, emerging paradigms such as the metaverse, adaptive avatars, and multimodal interaction open new horizons for creating cultural ecosystems where the physical and digital coexist harmoniously.

In conclusion, interactive museum experiences should be understood as living laboratories of cultural democracy. They enable societies to preserve the past, interpret the present, and imagine the future through accessible, immersive, and dialogic environments. By embracing innovation responsibly, museums can fulfill their mission as open platforms of lifelong learning and intercultural dialogue, ensuring that cultural heritage remains a shared and evolving resource for all [64–65].

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