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XR-based cultural heritage information spaces: Towards a new paradigm of information encoding and decoding guided by embodied cognition

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A R T I C L E I N F O

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A B S T R A C T

Embodied engagement in immersive information contexts is an emerging trend in informatics research. This study conceptualises XR-based cultural heritage information spaces as multimodal, open-ended environments shaped by embodied interaction. Based on a meta-synthesis of 67 empirical studies, we identify 22 core components and eight main categories across five dimensions of embodied interaction, forming a theoretical model of information flow and cognitive development in XR-based cultural heritage spaces. Embodied interaction is framed as a dual-phase information process: structured encoding of physical, sociocultural, and embodied elements, and user-driven decoding through emotional-aesthetic resonance and cognitive integration. The human body is positioned as an active human-computer interaction interface and processor, enabling the transformation of encoded content into self-constructed meaning. We propose a dual-path evaluation framework that combines system-level performance metrics with embodied-level cognitive and affective outcomes to assess interaction effectiveness. Furthermore, we highlight the role of physiological measures in capturing real-time user responses and enhancing the observability and interpretability of encoding-decoding dynamics. This study advances a human-centred perspective on information processing and offers actionable insights for analysing information behaviour in immersive environments.

1. Introduction

The rapid development of digital technologies has facilitated the evolution of methods for expressing and managing cultural heritage information. Cultural heritage informatics, situated at the crossroads of heritage, memory, and information, has attracted increasing attention from scholars. According to Modrow and Youngman's framework, cultural meanings are shaped through ongoing recontextualisation processes (Modrow & Youngman, 2023). These processes result from the interaction between an external context,

Abbreviations: VR, virtual reality; AR, augmented reality; MR, mixed reality; XR, extended reality; AI, artificial intelligence; 3D, three-dimensional; RFID, radio frequency identification; NFC, near field communication; fNIRS, functional near-infrared spectroscopy; EEG, electroencephalography.

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comprising tangible and intangible heritage, and an internal context, composed of personal memories and identity-related reflections. In this dynamic interaction, cultural heritage can be seen as a form of information shaped by time, rooted in the past, present, and connected to both individual and collective identities (Koya & Chowdhury, 2020). We call this dynamic, multi-layered information context the cultural heritage information space. It serves not only as a vessel for maintaining and creating cultural meaning but also as a key space for cultural experience and cognitive development (Urquhart et al., 2025).

With the integration of digital and intelligent technologies, GLAMs have increasingly integrated extended reality (XR) technologies into their exhibition strategies. This integration enhances the curatorial alignment between digital technologies and human perception channels in culturally impactful ways (Hou et al., 2022), offering a transformative opportunity to reconsider how such spaces are conceptualised and designed (Lin et al., 2025). Current technical systems characterised by enhanced visualisation, contextualisation, and interactivity (Gaugne et al., 2022; Zhang et al., 2025) may still fall short of effectively conveying cultural meanings and meeting the personalised needs of diverse users (Buckland, 2015; Hou et al., 2022). Embodied cognition theory offers a critical lens for understanding the construction of cultural heritage information spaces. This theoretical perspective posits that cognition is not an abstract process detached from the body but a 'perception-action' loop embedded within the continuous interaction between individuals and physical and sociocultural environments (Stephan et al., 2014). Consequently, constructing cultural heritage information spaces becomes not merely about displaying the past; it involves embodied-interaction-mediated scene reconstruction that renders the past perceptible, actionable, and reconfigurable. Cultural heritage informatics thus requires an updated theoretical framework and specific connotations.

Prior studies on XR-based cultural heritage information spaces have addressed the technological affordances and limitations of XR systems (Innocente et al., 2023), user experience design optimisation (Capece et al., 2024), and assessments of educational and learning outcomes (Anwar et al., 2025; Zhou et al., 2022). Some research has focused on cognitive-level concerns such as emotional design (Lin et al., 2025), the tacit knowledge–brain–cognition nexus in heritage conservation (Otero, 2024), the construction of embodied narrative meaning (Cunliffe & Coupland, 2012), and embodied information practices (Olsson, 2016; Olsson & Lloyd, 2017). However, these studies have rarely undertaken a systematic investigation of the construction mechanisms of XR-based cultural heritage information spaces through the lens of the embodied cognition theory. Moreover, few studies have examined in depth how macro- and micro-level mechanisms of embodied interaction manifest from the perspective of human-centred information processing.

Therefore, this study seeks to elucidate the mechanism for constructing cultural heritage information spaces by integrating theoretical deductions with case analysis. Considering the emerging challenges, opportunities, and pressing needs of XR technology in the processing, presentation, and experience of such spaces, we adopt embodied cognition theory as the core analytical framework, viewing the bodily dimensions of cognition and behaviour as the foundation for information processing. Through cultural heritage informatics, we further incorporate Hall's encoding/decoding model (Hall, 2007) to examine how XR-based cultural heritage information spaces—where the body underpins information processing—exhibit new characteristics and paradigms in information generation, dissemination, interpretation, and transformation. Guided by existing theories and the aims of this study, we articulate the construction mechanism through the following three research questions:

RQ1. *How are information encoding and decoding achieved in XR-based cultural heritage information spaces?*
RQ2. *How is the transition and transformation between information encoding and decoding facilitated in XR-based cultural heritage information spaces?*
RQ3. *How can the effectiveness of information encoding and decoding be measured in XR-based cultural heritage information spaces?*

To address the proposed research questions, this study conducts a meta-synthesis of 67 empirical studies, identifying 22 core components and five dimensions of cultural heritage information spaces. As a theory-oriented qualitative enquiry, it abstracts and integrates empirical insights to construct a conceptual model and dual-path evaluation framework for XR-based cultural heritage information spaces. Theoretically, this study advances the understanding of how embodiment mediates the encoding and decoding of cultural heritage information. Practically, it offers a structured foundation for designing, evaluating, and optimising embodied interactions in immersive heritage environments. By framing the human body as both a nexus of perception, action, and interpretation and an interface for human-computer interaction, the study repositions embodiment as central to the dynamic formation of cultural heritage information spaces, fostering richer cross-cultural interpretation and experiential engagement.

The remainder of this paper is organised as follows. Section 2 reviews prior research on embodied cognition and Hall's encoding/decoding model, including studies on information behaviour, and identifies research gaps. Section 3 describes the methodology used in this study, including data collection, extraction, and analysis. Section 4 presents the results of the meta-analysis. Section 5 discusses the components of the information encoding and decoding processes and evaluation methods based on the findings. Section 6 concludes the study and highlights its contributions and limitations.

2. Theoretical basis

2.1. Embodied cognition

Embodied cognition theory posits that cognitive and bodily processes are co-constitutive: individuals come to understand and adapt to the world through a continuous perception-action loop, enabled by the sensory-motor capacities of the body and its coupling with both natural and sociocultural contexts (Kiverstein, 2012). Individuals engage with their surroundings through multisensory perception, embodied movement, and tool-mediated interaction. These sensory and motor activities form a dynamic cycle in which individuals perceive environmental changes, respond, and adjust their understanding based on the feedback from these actions. Related theoretical branches such as technological embodiment and embodied interaction have emerged with the rapid advancement of technology, particularly driven by the emergence of immersive technologies such as virtual reality (VR), augmented reality (AR), and mixed reality (MR), which reflect a theoretical adaptation to new information spaces. These propositions emphasise that perception is enacted through direct interaction with technologies, environmental interpretation relies on the system's operational opacity (Ihde, 1990), and embodied interaction is deeply embedded in sociocultural contexts (Anderson, 2003). These theoretical developments suggest that, although embodied interaction has traditionally depended on real-world temporality and spatiality, XR-based virtual environments, when conceptualised as metaphoric extensions of real-world interaction, can afford individuals the capacity to engage with their surroundings through perception and action. The interpretive agency of individuals thereby becomes more pronounced, allowing for diverse, personalised understandings of cultural symbols as well as the physical and social dimensions of space (Zhang & Xu, 2024). Together, these perspectives offer a robust foundation for rethinking cognition as a socio-culturally situated, technologically mediated, and bodily enacted phenomenon (Dourish, 2001; Glenberg, 1997a; Lakoff, 2008).

Building on this recognition, the concept of embodiment has been widely incorporated into studies on information behaviour (Lueg, 2015; P. Lueg, 2014; Tschacher & Bergomi, 2015) and information practice (Cox et al., 2017; Olsson, 2016; Polkinghorne, 2021). Specifically, research has shown that contextual variables in information behaviour such as prior experience, knowledge levels, and personal preferences, as well as cognitive factors such as immersion, sense-making, and memory, are closely intertwined with embodied interaction (Barry, 1994; Keilty, 2012). Embodiment also reflects the dual nature of information practice: it is both socially situated and biologically grounded (Olsson, 2016), offering a valuable perspective for examining the roles of materiality and agency in meaning-making processes. Importantly, Merleau-Ponty's early semiotic model (symbolism) of the relationship between the mind and the world continues to inform contemporary enquiries into the intersection of embodiment and information. This model emphasises that perceptions and actions must be expressed through embodied representations to generate symbolic meaning (symbolique) (Merleau-Ponty, 2013). Within this embodied-symbolic relationship, humans, through actions, acquire semiotic significance and turn perceptual objects into reframed cognitive themes, which offer a semiotic framework for interpreting information behaviour. The framework of embodied cognition aligns here with cultural heritage informatics, providing a theoretical basis for analysing how cultural heritage information is deconstructed, activated, and expanded through the interplay between external and internal contexts (Foglia & Wilson, 2013; Not & Petrelli, 2018).

Overall, the embodied cognition theory aligns with the human-centred principles emphasised in cultural heritage experiences, highlighting that the value of heritage lies not only in its material form but also in its dynamic interactions with people and their sociocultural environments. Cultural heritage is not merely a static, material entity but a dynamic cultural practice—an evolving narrative co-constructed through collective and individual experiences of emotion, memory, and identity. XR-mediated embodied interaction enables deeper interpretive engagement by facilitating dynamic exchanges and spatial feedback between users and heritage entities (Sylaiou et al., 2024). The resulting embodied information refers to the information received through the senses and the way the body acts as a sign that others can read (Cox et al., 2017). It not only reinterprets and reframes original cultural meanings, but also constitutes a new and integral layer of XR-based cultural heritage information spaces. Through bodily engagement, individuals establish deeper cognitive connections with cultural heritage, enabling a more layered and meaningful interpretation of heritage information. In doing so, individuals become active participants in the co-construction of cultural meaning within these information spaces, facilitating group-based collaborative learning (Danish et al., 2020). Thus, the embodied cognition theory provides a robust theoretical foundation for understanding how XR-based cultural heritage information spaces are conceptualised and experienced.

2.2. Encoding/decoding model

Hall introduced the encoding/decoding theory in 1973 (Hall, 2007). In this framework, information can be understood as a sign-vehicle, or more precisely, a structured set of signifiers organised through codes and embedded within the syntagmatic chains of discourse. Communication is conceptualised as a cultural process comprising three interrelated phases: encoding, circulation, and decoding (Hall, 2019). Encoding refers to the process by which producers structure and organise raw materials into media texts designed to be resonant and intelligible within particular symbolic systems. Decoding involves users actively interpreting messages by drawing on their cultural frameworks and experiences. Encoding and decoding are connected through the process of circulation. Beyond these three stages, there is an additional, implicit phase referred to as the 'reproduction stage'. In this phase, users generate reinterpretations and feedback on meaning, and may even produce entirely new texts (Xie et al., 2022). Central to this model is the notion of 'codes'—the symbolic form of the message which is not a direct reflection of reality, but structured systems of meaning created and deployed by encoders within the communicative process. Within Hall's framework, the codes employed during encoding and decoding are not necessarily symmetrical. The extent of alignment between encoded and decoded meanings depends not only on shared cultural understanding between encoders and decoders, but also on the degree of identity between the respective coding systems. Such asymmetries often give rise to misinterpretations, revealing the role of selective perceptions shaped by differing ideological, cognitive, and contextual frames. Encoding and decoding are further mediated by an established set of regulatory conventions and 'encoding rules' that structure both the representational form and interpretive potential of messages. In the manner that historical events are mediated through the audiovisual language of media, the representation of cultural heritage depends on complex encoding rules and multimodal codes that enable cultural meanings to be symbolically structured and transmitted, thereby establishing specific interactional mechanisms (Lin et al., 2025).

Hall's encoding/decoding model offers a valuable analytical framework for examining how cultural heritage is communicated, interpreted, and recontextualised across media platforms. Scholars have applied this framework to investigate how cultural heritage is encoded in digital media (Park & Su, 2024), how key historical terms are translated and redefined in specific temporal contexts (Conway, 2017), and how encoded narratives influence public identification with and participation in heritage discourses (Dicks, 2000; Wang, 2014). With the rise of XR technologies, Hall's model has been reinterpreted to address new forms of embodied media (Bødker, 2018; de Wildt et al., 2024). In immersive environments, users engage with information not only through visual and auditory channels, but also through bodily movements, spatial navigation, and interaction with simulated environments (Weissenberger et al., 2018). On the one hand, these forms of engagement extend the traditional encoding/decoding framework by incorporating cognitive, sensory, embodied, and affective dimensions, offering critical insights into the constitutive elements and interaction mechanisms of XR-based cultural heritage spaces. On the other hand, from the perspective of cultural heritage informatics, heritage is not merely a record of tangible or intangible assets; rather, it is fundamentally an informational phenomenon serving as a vehicle for transmitting memory across time, thereby sustaining both individual and collective identities. Within XR environments, the cultural heritage experience involves the selection, translation, and recombination of heritage information in new contexts and processes that closely mirror the mechanisms of information selection, integration, and re-encoding described in cultural heritage informatics. Thus, Hall's encoding/decoding model offers a compelling framework for understanding the processing of cultural heritage information and provides a valuable reference for conceptualising the two-phase construction process of XR-based cultural heritage information spaces.

3. Methods

This study employed the meta-synthesis method to collect and analyse relevant literature, combined with inductive coding based on grounded theory, to extract, organise, and conceptualise the data. Meta-synthesis involves synthesising findings from existing empirical studies to generate new theoretical insights beyond individual cases. It typically includes four stages: literature search, determination of inclusion and exclusion criteria, literature evaluation, and data extraction and analysis (Catalano, 2013; Edwards & Kaimal, 2016). This study adopted meta-synthesis because of its demonstrated effectiveness in constructing higher-order conceptual frameworks from fragmented empirical findings, particularly in interdisciplinary and emerging fields where theoretical development remains nascent (Campbell, 2011; Chrastina, 2018). Given the dispersed nature of the existing research on XR-based cultural heritage information spaces and the lack of unified theoretical models, meta-synthesis provides a systematic, theory-oriented approach for identifying the core elements and mechanisms underlying embodied interaction in XR environments. The empirical studies synthesised in this study also serve as case-based validations of the theoretical propositions advanced. By synthesising 67 empirical studies, this research offers a comprehensive and conceptually grounded understanding of this phenomenon. We conducted a comprehensive search, screened and evaluated relevant studies, and analysed the selected materials using grounded theory methods. Grounded theory is a rigorous qualitative methodology designed to generate theoretical insights directly from empirical data (Strauss, 1987). Employing open, axial, and selective coding, we extracted the key concepts and constructed a theoretical model explaining the embodied interaction mechanism in XR environments for cultural heritage. This integrated methodological approach supports the development of a robust theory-driven framework to explain embodied information behaviour in immersive cultural heritage environments.

3.1. Data collection

3.1.1. Inclusion/exclusion criteria

To ensure systematic data collection and conceptual rigor, we established clear inclusion and exclusion criteria for selecting the literature for meta-synthesis. Studies were included if they met the following criteria.

(1) they were explicitly grounded in embodied cognition theory, either as a central theoretical framework or key interpretive lens.
(2) they reported exploratory or validating empirical findings, defined as research that either (a) employed exploratory qualitative methods (e.g., case studies, ethnography, interviews, observational analysis) to identify themes, user perceptions, or interactional mechanisms in XR environments for cultural heritage, or (b) used validating quantitative methods (e.g., experimental designs, surveys, usability testing) to test or measure embodied experience constructs, interaction outcomes, or user engagement metrics. These definitions align with the typologies described by Creswell (2017). Mixed methods studies were included if they presented an articulated sequential design, where either qualitative data informed subsequent quantitative inquiry (exploratory sequential) or quantitative results were explained through qualitative follow-up (explanatory sequential).
(3) The content specifically addressed XR cultural heritage experiences, including virtual reality (VR), augmented reality (AR), or mixed reality (MR);
(4) The publication date fell between January 1, 2005, and December 31, 2024;
(5) The study was published in English in peer-reviewed journals, conference proceedings, or academic dissertations. If redundant versions of the same study were found (e.g., conference paper, journal article, and dissertation by the same author), only the most complete version was included to avoid duplication.

3.1.2. Search strategy

To identify relevant studies, keywords were developed based on three thematic domains: embodiment, cultural heritage, and extended reality. The embodiment-related terms included 'embodied', 'embodiment', and 'embody'. For cultural heritage, keywords such as 'cultural heritage', 'cultural artefact', 'cultural artefact', 'cultural object', 'cultural relic', and 'cultural site' were used. These terms were selected because of their frequent interchangeable use in existing literature, despite occasional inconsistencies. Search queries were formulated based on these keywords and applied across four primary databases: Web of Science Core Collection, Scopus, ProQuest Dissertations, Theses Global, and arXiv. Google Scholar was also used for snowball sampling to identify studies that were potentially overlooked owing to keyword limitations. The selection process is illustrated in Fig. 1. The selected databases and the resulting search string are detailed in Table S1.

3.2. Data extraction and analysis

Following the literature selection process, the full texts of the included articles were imported into MAXQDA 24 for inductive coding. Sections on the methods, results, and discussion were extracted for analysis, whereas purely theoretical or review-based content was excluded. The coding process was guided by grounded theory to conceptualising, categorising, and integrating the data to identify key patterns and relationships. Two researchers independently coded a subset of four articles to establish the initial coding consistency. Inter-coder disagreements were resolved through iterative discussions until a consensus was reached. In the final stage of the analysis, an additional 12 articles were set aside for theoretical saturation testing.

4. Results

4.1. Descriptive statistical results

This review examines 67 empirical studies published between 2009 and 2024, comprising 26 journal articles, 35 conference papers, and six dissertations. The characteristics of the included studies are presented in Table S2. The corpus reflects a strong cross-disciplinary orientation, with the natural sciences contributing primarily to computer science and neuroscience, while the humanities and social sciences draw on history, art, religion, psychology, and information science. Studies are distributed relatively evenly across tangible and intangible cultural heritage, with a notable number engaging in both (Fig. 2a). Sites, routes, movable heritage, and museum artefacts dominate the tangible categories, whereas oral traditions and expressions are the most common among the intangible categories (Table 1). VR is the most frequently employed technology, followed by AR and MR (Fig. 2b). Following Creswell's typology (Creswell, 2017), the studies were classified into quantitative, qualitative, and mixed-methods (Fig. 3). Qualitative approaches prevail, with interviews, observations, and case studies as the most common techniques. In quantitative design, surveys are predominant. Meanwhile, a rise in mixed methods research is apparent, reflecting growing interest in triangulating subjective experiences with objective indicators of sensory, cognitive, and emotional engagement.

4.2. Inductive coding results

Through a grounded theory analysis, we conducted a three-phase coding process to extract and organise the core components of embodied interaction in XR environments for cultural heritage purposes. Open coding generated 72 initial concepts (a1–a72), which were iteratively refined and consolidated into 22 categories (A1–A22) as detailed in Tables S3 and S4 of the Supplementary Materials. Axial coding grouped these categories into eight main categories across five dimensions—stakeholders, digital technologies, grounded processing, measuring methods, significance, and limitations— as summarised in Table 2. In the final stage, selective coding was used to identify the interrelationships between these categories, which provided the foundation for constructing a conceptual model. These relationships are shown in Fig. 4, with further explanations provided in Table S5 in the Supplementary Materials.

5. Discussion

The theoretical model was obtained by combining grounded theory and the coding results with embodied cognition theory and the encoding/decoding model (Fig. 5). It provides an integrated framework for understanding and implementing XR-based cultural heritage information spaces. We conceptualise the embodied interaction in XR environments for cultural heritage as a complete process, from encoding cultural heritage information to decoding by users. The dynamic interplay between embodied elements and physical and sociocultural environments jointly shapes the cultural heritage information space.

Drawing on Hall's encoding/decoding model, this study operationalises the abstract notion of embodied cognition as a two-stage information processing framework: structured encoding of physical, sociocultural, and embodied elements, followed by user-centred decoding through emotional-aesthetic resonance and cognitive integration. In this integration, embodied cognition informs the content and modalities of encoding by embedding sensory, bodily, and socio-material experiences, whereas the encoding-decoding model provides a systematic structure that externalises these embodied processes from an implicit mental phenomenon into an explicit mechanism of information production and understanding. By formulating tightly coded 'rules of encoding', cultural meaning is likely to be decoded in a manner that is highly symmetrical to that in which it is encoded. Therefore, this reciprocal relationship allows the framework to serve as both a conceptual lens and an operational tool for analysing how shared practical insight emerges from becoming or being embodied in context.

However, in XR-based cultural heritage spaces characterised by high fidelity, strong interactivity, and spatial expansiveness, embodied cognition introduces novel components into each stage of the encoding–decoding process, signalling a paradigm shift. In the encoding stage, the framework retains the physical environment elements—termed 'material substratum' in Hall's original model (e.g., cultural heritage objects and historical scenes)—while introducing two additional categories of elements based on embodiment theory: sociocultural environment elements (e.g., historical facts and sociocultural values) and embodied elements (e.g., body image

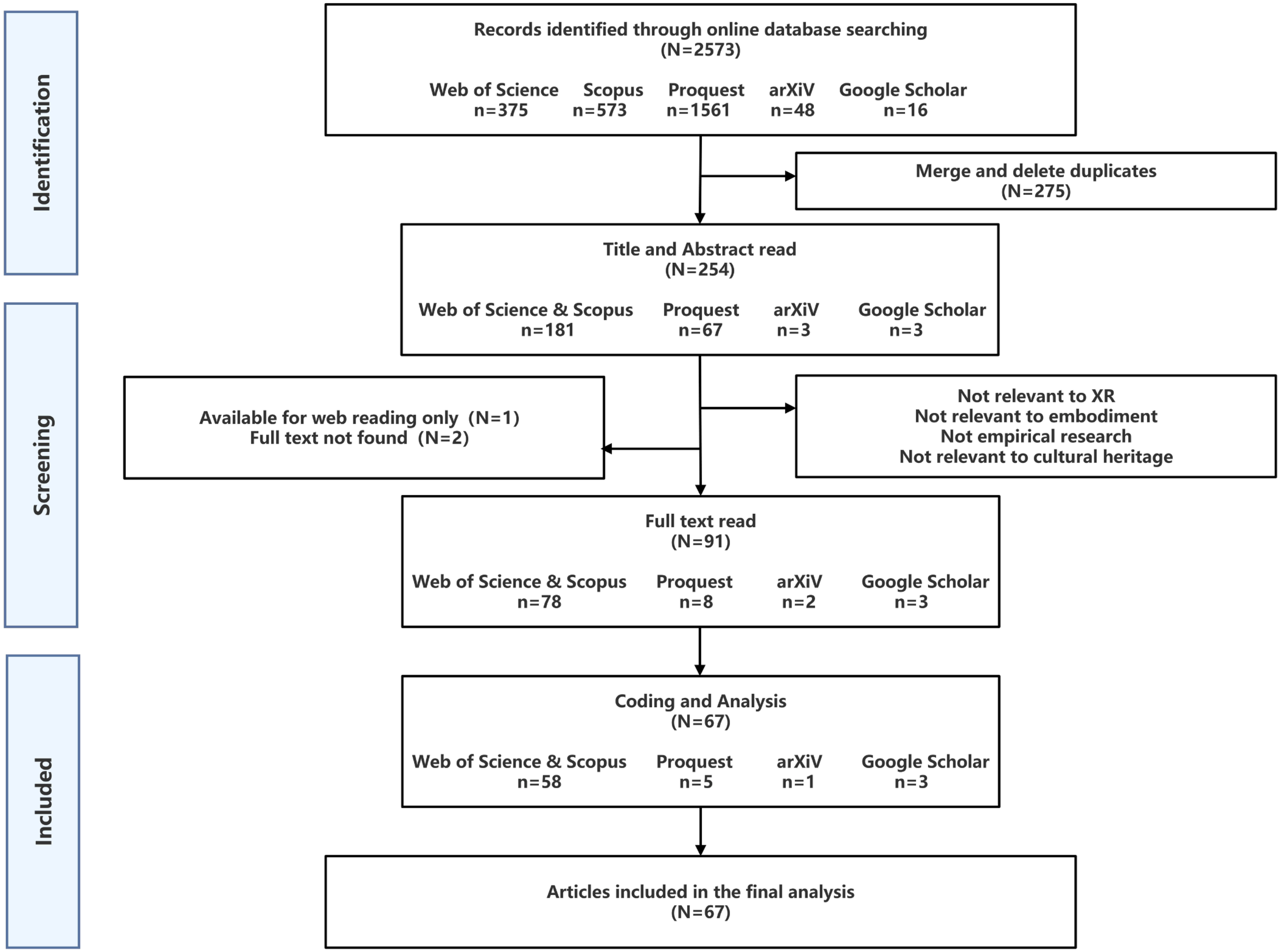

Fig. 1. Selection and analysis process.

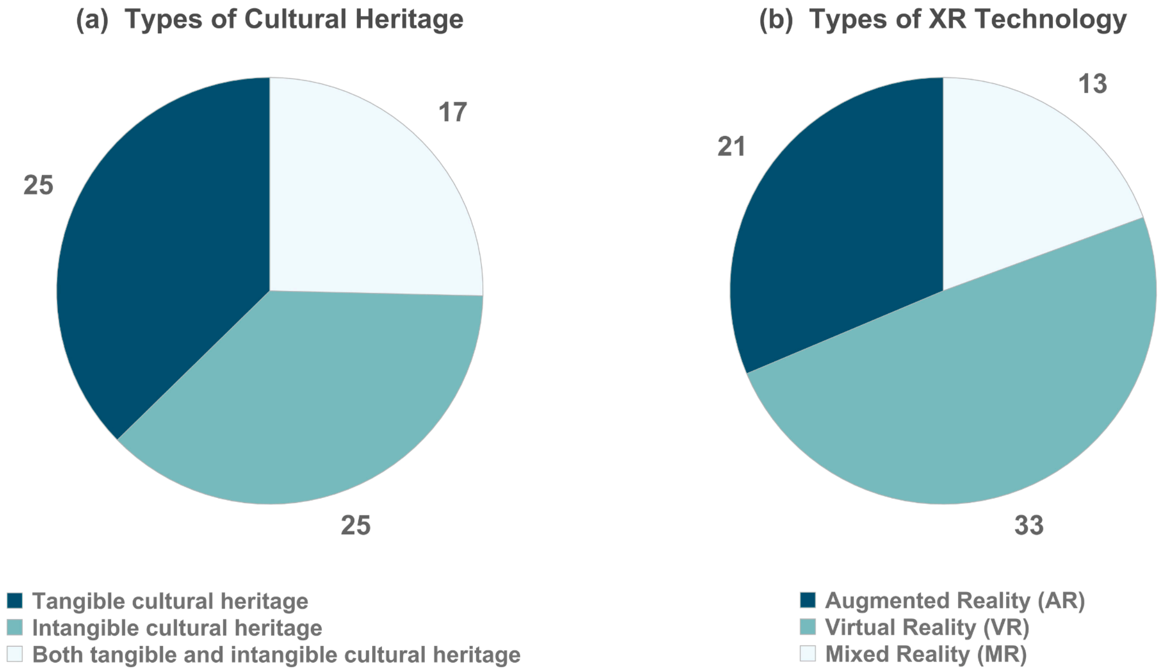

Fig. 2. Types of cultural heritage and XR technology in the included studies.

Table 1
Distribution of cultural heritage types and sub-categories in the included studies.

Heritage type	Sub-category	Number of studies
Tangible	Movable heritage and museum artefacts	14
	Sites and routes	26
	Artworks	8
	Traditional craftsmanship	12
Intangible	Oral tradition and expressions	14
	Social practices, rituals, and festivals	5
	Performing arts	5

and body schema). In the decoding stage, the incorporation of embodiment theory extends the reproduction stage implicit in Hall's model, yielding two new user decoding pathways: emotional resonance facilitated by aesthetic interpretation, and cognitive development fostered through meaning-making. This shift underscores how decoding is shaped predominantly by social discourse, rather than entirely dictated by cultural codes or linguistic symbols, thereby transforming it into a more open and polysemous discursive system.

Within this redefined paradigm, the body is not merely a carrier of cultural codes but also functions as a central interface and processor in information processing, actively mediating between the physical and sociocultural environment and meaning-making. Positioning the body as both a generator and interpreter of information is a substantive departure from either framework in isolation, fostering the emergence of a genuinely new paradigm.

The following section elaborates on how the proposed model addresses *RQ1–RQ3*. Sections 5.1 and 5.2 focus on information encoding and decoding, Section 5.3 examines the processes connecting them, and Section 5.4 proposes an interdisciplinary evaluation framework grounded in embodied cognition.

5.1. RQ1: model of information encoding

In the context of information dissemination, encoding refers to the structuring of meaning through symbolic representation, whereas decoding involves users' interpretation and reconstruction of symbols (Hall, 2007). As a socially recognised and value-laden domain (Krakow, 2000), cultural heritage, owing to its inherent complexity, requires multidimensional encoding processes that integrate natural descriptions, conventional interpretations, and intrinsic meanings to facilitate deeper knowledge discovery (Wang et al., 2018). Traditional cultural heritage information encoding approaches often fail to capture complex cultural ecologies, particularly regarding scenario construction, non-linear storytelling, and active audience engagement (Carrozzino et al., 2011). Integrating embodiment offers a novel pathway for encoding cultural meaning. By framing bodily movement as an embodied metaphor, the

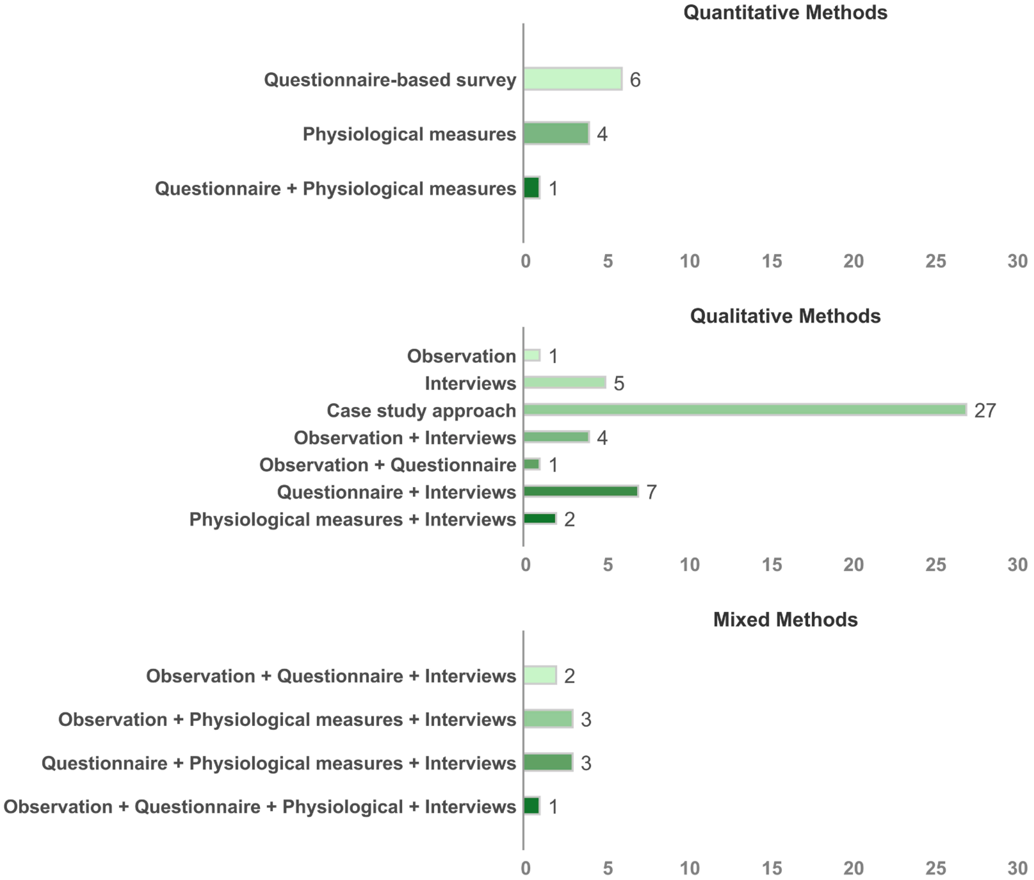

Fig. 3. Types and frequencies of data collection methods used.

Table 2
Results of axial coding.

Dimension	Main category	Category
Stakeholders	Cultural heritage objects	A1 tangible cultural heritage
		A2 intangible cultural heritage
	Diverse communities	A3 broad user groups
		A4 specific user groups
Digital Technologies	Implementation techniques	A10 intelligent technologies
		A11 interactive technologies
		A12 production and display technologies
		A13 foundational technologies
Grounded Processing	Core elements	A5 multisensory experience
		A6 artefacts
		A7 scene simulation
		A8 characters
		A9 narrative strategies
	User cognition	A15 emotional resonance and aesthetic interpretation
		A16 cognitive development and meaning-making
Measuring Methods	Research methods and measurements	A14 evaluation methods
Significance and Limitations	Sociocultural value	A17 social value and public engagement
		A18 cultural heritage transmission and innovation
	Limitations	A19 limitations in experience processes
		A20 limitations in narrative design
		A21 limitations in technical implementation
		A22 limitations in sustainable usage

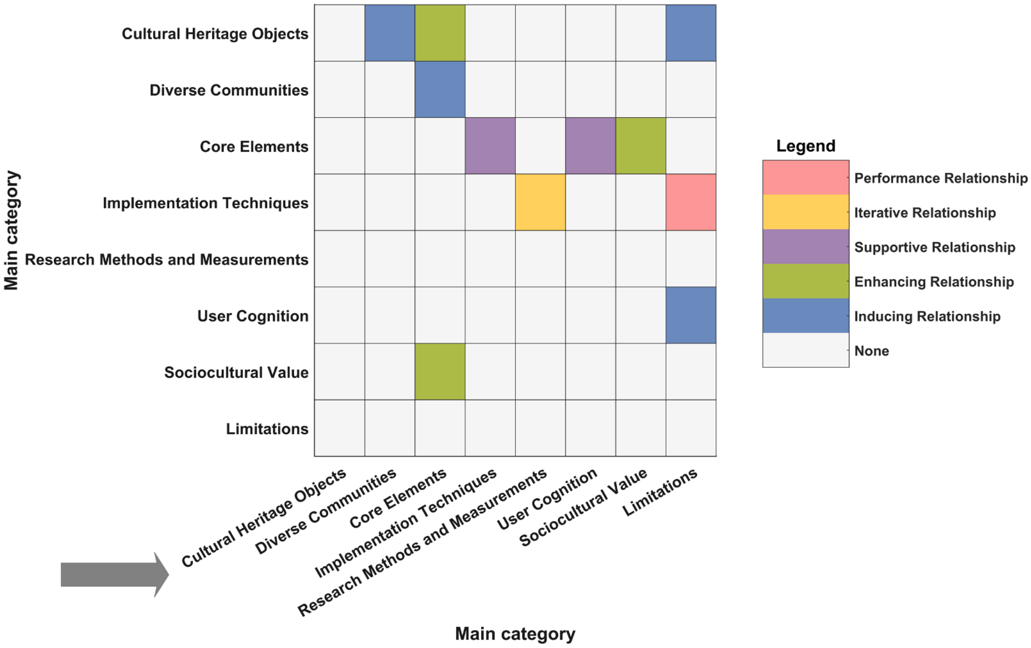

Fig. 4. Matrix of interrelationships among main categories.

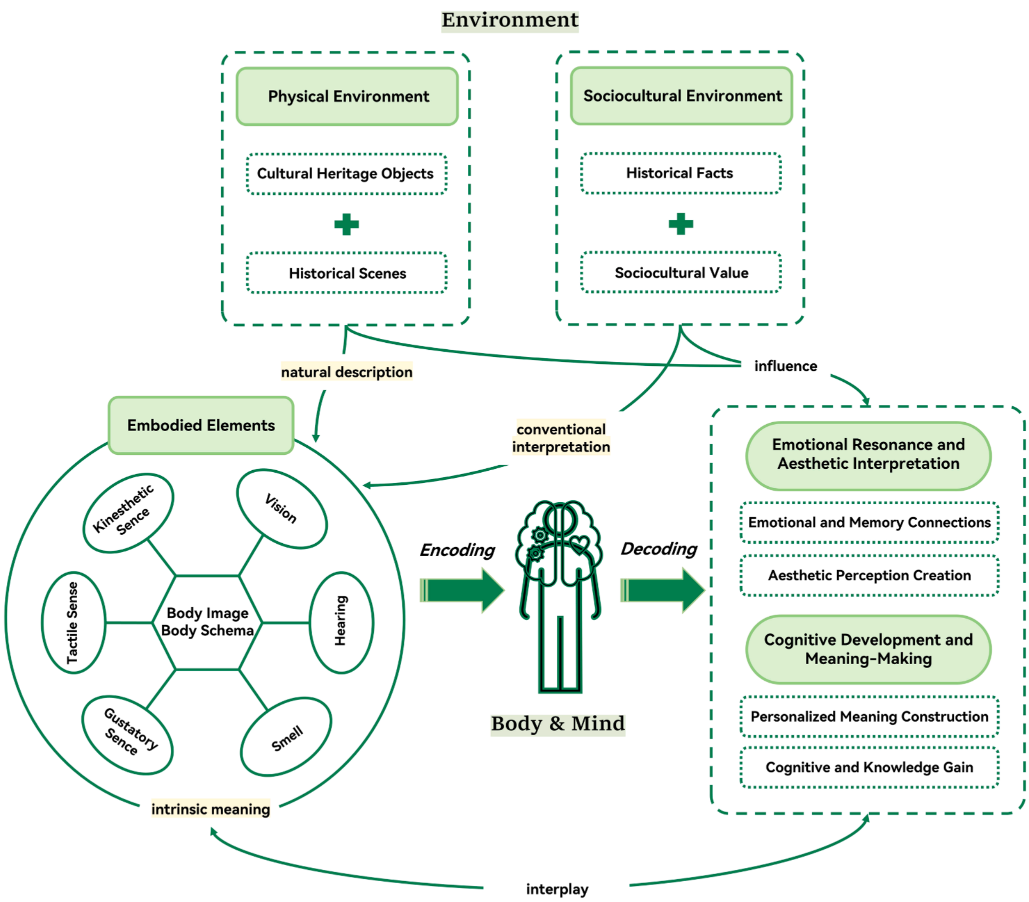

Fig. 5. Theoretical model of embodied interaction mechanism in XR environments for cultural heritage.

sensory experience serves as a catalyst for creative cognition (Niedenthal, 2007; Wilson, 2002). Encoding becomes not only a semiotic activity but also a bodily, participatory cognitive process. Embodied encoding in XR-based cultural heritage information spaces refers to the use of digital and intelligent technologies to extract and translate relevant physical, sociocultural, and embodied elements into multimodal formats, including images, text, audio, video, body images, and body schemas, which are then used to construct in-person scenarios and design narrative strategies grounded in cultural meanings (Hou et al., 2022).

Based on our coding analysis, we classify the encoded elements of cultural heritage information into three categories: physical environment, sociocultural environment, and embodied elements, which correspond to the natural description, conventional interpretation, and intrinsic meaning of heritage, respectively. The first two categories reflect the physical and cultural complexity of the heritage object and its context, while embodied elements emphasise the user's sensory and physical engagement and underscore the unique characteristics of embodied encoding in XR environments. Together, these elements form an interrelated and layered structure that drives the process of encoding cultural heritage information.

5.1.1. Physical environment elements

Physical environment elements refer to cultural heritage objects and their associated historical settings. This category corresponds to the natural description dimension of cultural heritage information, and involves the features immediately perceivable and thematically inherent to an object. For tangible heritage, encoding begins with close observation of its unique visual characteristics, including colour, texture, shape, composition, material components, and preservation conditions (Dima & Maples, 2021). For intangible heritage, intricate processes, craft traditions, and narratives embedded in tacit knowledge must be considered (Wang et al., 2018). Artefacts—man-made representations of heritage entities—serve not only as carriers of cultural information, but also as mediators that trigger embodied actions, playing a critical role in guiding user engagement in XR environments (Triberti & Brivio, 2017). Artefacts can be broadly categorised into two types: smart objects (e.g. 3D-printed replicas and props embedded with RFID/NFC sensors) and digital interfaces (e.g. multi-touch screens or mobile applications). These artefacts embed curated heritage content and predefined interaction protocols. Within narrative-driven XR scenarios, they serve as anchors for subsequent decoding, shaping how users perceive and interact with cultural information (Not et al., 2017). However, the design of artefacts and their associated interaction behaviours must consider factors related to physical affordances such as the grip comfort of handheld props or controllers (Galeazzi et al., 2015; Loder, 2021) and the tactile realism of the reproduced objects (Galeazzi et al., 2015), which directly affect the naturalness and intuitiveness of user interaction.

As heritage entities cannot be meaningfully represented apart from their historical scenes, encoding requires reconstructing spatial relationships, particularly time and location, through spatial orientation, topological structure, and spatial semantics. Scene simulation, a key component of physical environment encoding, requires an alignment between a cultural heritage object and its original historical context (Guo et al., 2024; Ijaz, 2011). Such simulations typically reflect hybrid physical–digital environments built collaboratively through fixed installations (e.g., touchscreens, interactive kiosks) and mobile devices (e.g., smartphones, tablets) (Capece et al., 2024). To enhance immersion and cultural situatedness, multiple strategies are employed, including multisensory experiences, temporal sequencing, and game-based scenarios (Guo et al., 2024; Loder, 2021; Volkmar et al., 2018). Multisensory experience acts as a perceptual bridge between physical environment elements and user decoding, engaging multiple sensory modalities to evoke historical contexts with maximal vividness (Pietroni et al., 2012). For instance, tactile feedback can convey the temperature and texture of architectural surfaces, acoustic spatialisation enhances environmental realism and auditory orientation (Flynn, 2013), while olfactory and gustatory cues evoke atmospheric associations with the historical period (Mazzucato & Argiuolo, 2021). Informational overlays or metadata panels, in real or virtual environments, often serve as cognitive scaffolds that facilitate users' initial perceptual engagement with the information space. This contributes to users' understanding of technological aspects (e.g. how the object was created, transported, and displayed), compositional features (e.g. materiality and structure), and contexts that shape its historical significance (Rose, 2022). However, designing historically grounded XR scenes also involves negotiating a trade-off between cultural authenticity and interaction quality (Bekele et al., 2018; Boboc et al., 2022). Research indicates that, in virtual environments, perceived credibility often outweighs visual accuracy, as excessive realism can compromise system performance and diminish user engagement (Loder, 2021). Therefore, encoders must strategically calibrate scene rendering to balance immersive engagement with the preservation of historical integrity.

5.1.2. Sociocultural environment elements

Sociocultural environmental elements refer to encoded representations of historical realities reflected in cultural heritage objects, including historical actors, causal relationships, unfolding processes, outcomes, and sociocultural identities and values. This category aligns with the conventional interpretation of cultural heritage information, which focuses on meanings derived from stories or events conveyed by cultural heritage sites. Heritage entities exist as objective realities without narrative processing or modification, providing raw semantic materials that link time, place, people, artefacts, and events—materials from which backgrounds, causal frameworks, pivotal moments, and conclusions can be extracted and organised into encoded content. This encoding layer offers a cognitively flexible and open interpretive space that accommodates diverse user perspectives, which helps bridge the interpretive gap that may emerge as users transition from surface-level observations to deeper immersion within XR-based cultural heritage information spaces.

Encoding sociocultural environmental elements often begins with semantic materials that are contextually associated with cultural heritage objects, providing evidentiary grounding for historical facts (Fan & Wang, 2022). These materials are primarily drawn from archival collections curated by museums, encompassing official sources such as military records, government decrees, legal documents, and personal accounts, including letters, diaries, and other first-hand narratives and historical media sources, including period texts, radio broadcasts, and video footage (Marshall et al., 2016). Through digital and intelligent technologies, these materials are artistically visualised—such as in re-enactment scripts enriched with sound design and dialogue—and subsequently integrated into interactive systems through embodied design approaches (Kenderdine et al., 2021).

In terms of encoding strategies, virtual characters and their associated modes of interaction serve as critical connectors for integrating materials related to cultural heritage objects. In XR-based cultural heritage information spaces, users can engage with the environment by adopting virtual identities (Chu et al., 2016; Li et al., 2024), communicating with non-player characters (NPCs) (Bollini & Borsotti, 2023; Ma et al., 2023; Neto et al., 2015), or participating in social collaboration with other users (Kenderdine et al., 2009; Lucifora et al., 2023). Empirical studies indicate that users value brief moments of social interaction in immersive environments and often seek such experiences. These findings suggest that character-driven interaction design is pivotal in enhancing social presence and cultural belonging (Flynn, 2013; Nemcova et al., 2023), reducing feelings of isolation (Galani & Kidd, 2019), and fostering community-oriented experiences in virtual heritage settings. This approach reflects a form of culturally situated discourse that enables the presentation of people and events embedded in heritage entities in ways that align with users' cognitive schemas and interpretive expectations. As broader sociocultural contexts, including politics, economic systems, religious practices, social routines, and customs are made intelligible and experientially accessible, the role of embodiment in facilitating users' comprehension of sociocultural contexts has been underscored.

5.1.3. Embodied elements

Historically, symbolic encoding often rendered the human body absent, positioning it as an implicit or invisible subject within a representational system. Under the framework of symbolism, the body becomes a symbol of expression and a perceptual structure imbued with meaning, the interpretation of which depends on a deep internal representation. Encoding embodied elements entails turning the user's body and actions into a body image and body schema, which form two complementary layers of internal bodily representation: perceptual structure and functional reference for movement (Matsumiya, 2022). Motor planning relies on a unified body representation that allows individuals to perceive and act through their bodies as coherent entities. Therefore, we can digitally model and encode these embodied representations in XR environments, enabling the externalisation of implicit cultural knowledge through gestures, movements, and dialogue. This process supports the symbolic transformation of body perception, positioning the user as an active and visible agent in cultural heritage information spaces.

Specifically, body image encoding focuses on a user's observable physical characteristics, including body shape, posture, facial features, and skin tone. A virtual avatar is created to represent the user's body in an XR environment based on these fundamental attributes. Depending on the scenario, motion capture technologies can provide real-time mirroring and responsive feedback, projecting a user's physical presence onto virtual environments as a perceptible digital surrogate. Notable here is the surrogate shadow strategy, which generates three slightly varying pre-rendered humanoid silhouettes for each user. These silhouettes are dynamically projected onto a screen and adjust in response to the user's physical movements, enhancing spatial orientation and the sense of environmental immersion (Flynn, 2013). Research suggests that virtual avatars in cultural exhibitions can significantly boost children's engagement and enhance their recall of visual details associated with the artwork (Rehm & Jensen, 2015), underscoring the potential of avatar-based embodiment in strengthening attention and memory in immersive heritage experiences.

Body schema refers to the brain's dynamic spatial representation of different parts of the body, which continuously adapts to changes in bodily form and movement. They play a critical role in motor control by unconsciously regulating posture and actions, thereby integrating sensory and environmental information into coherent embodied experiences. In XR-based cultural heritage information spaces, body schema encoding involves the visual feedback of self-initiated motion and holistic awareness of one's bodily posture in a multisensory environment (Merleau-Ponty et al., 2013). A key aspect involves designing embodied interactive behaviours aligned with afferent signals (sensory feedback on body posture) and efferent copies of motor commands (predicted movement outcomes) (Paillard, 1999). Complex embodied behaviours often incorporate gamification or participatory performance supported by real-time NPC feedback such as cheering or applause. Such strategies have been shown to enhance sustained user engagement and stimulate users' motivation for heritage exploration (Zhang & Bryan-Kinns, 2022). Simple embodied behaviours include basic yet meaningful interactions such as clicking or dragging tags (Chu & Mazalek, 2019), adjusting the viewing angle (Ji et al., 2021), swinging limbs (Volpe & Camurri, 2011), grasping or throwing virtual objects (Oh & Shi, 2021), and speaking with virtual agents (Ijaz, 2011). Although less complex, these interactions foster a progressive cultural understanding through subtle bodily engagement. Another particularly effective pathway for body schema encoding is kinesthetic sense awareness of bodily movement. When combined with motion capture and physiological computing, kinesthetic inputs can trigger symbolic visual feedback (e.g. dynamic imagery responsive to motion) (Guo et al., 2024). Additionally, raycasting mechanisms—often used in VR to represent users' intention via a visual pointer—serve as embodied extensions of the user's body, enabling real-time interaction with virtual heritage objects and characters (He, 2023; Ma et al., 2023), translating abstract bodily movement into visible, interpretable forms. Ultimately, body schema encoding recentres cultural meaning in the individual, transforming the user's body into a legible and responsive symbol within the immersive experience. Instead of perceiving themselves as mechanical components of a system, users begin to think of themselves as self-aware, embodied agents situated in the 'here and now', thus revealing a sense of ownership and agency (Shimada, 2022).

5.2. RQ1: model of information decoding

The user interpretation of cultural heritage information constitutes the central component of embodied interaction in XR environments. Decoding refers to the user's process of engaging with and internalising cultural information through embodied experiences, transforming sensory and behavioural inputs into emotional resonance and conceptual understanding. Importantly, decoding is not a passive reception of meaning but an active, interpretive process rooted in users' prior experiences, cognitive schemas, and cultural positioning. As Hall's model of dominant, negotiated, and oppositional readings suggests, decoding reflects a spectrum of subjective meaning constructions rather than a fixed response (Hall, 2007). Embodied decoding in XR-based cultural heritage information spaces is a process in which users recognise, interpret, and make sense of the encoded symbolic content by integrating perceptual input and existing knowledge. This process enables a transition from symbol to information to meaning, ultimately facilitating deeper insight and personalised meaning making. Whether through sensorimotor or symbolic reconstruction modes, decoding is inherently dynamic and dialogic (Pietroni et al., 2012). It emphasises not only cognitive engagement with symbolic content, but also the active construction of meaning through interactive experience. Compared with encoding, decoding operates more as an invitation for users to engage in a co-constructive process of cultural interpretation. As illustrated in Fig. 5, the decoding mechanism follows two intertwined pathways. The first centres on emotional resonance and aesthetic interpretation, where meaning emerges through the embodied coupling of emotion and perception. The second emphasises cognitive development and individual meaning-making, highlighting users' active roles in reconstructing cultural significance. These dual dimensions together reflect the layered complexity and depth of the embodied decoding in XR-based cultural heritage information spaces.

5.2.1. Emotional resonance and aesthetic interpretation

Emotional resonance and aesthetic interpretation represent key outcomes of the decoding process in XR-based cultural heritage information spaces. Based on embodied cognition theory, this dimension emphasises that direct experiential engagement with historically meaningful content is critical for fostering users' affective connections with cultural heritage (Niedenthal, 2007; Oleksy & Wnuk, 2016). Unlike traditional passive viewing, embodied interaction enables users to actively engage in performative activities, enhancing the retention of cultural knowledge, and enabling a more vivid and emotionally engaging transmission of historical narratives (Ji et al., 2023; Loder, 2021). For instance, NPC-guided interactions or task-driven cues (Liu et al., 2022; Neto et al., 2015) can strengthen emotional ties between users and specific virtual characters or scenes (Nemcova et al., 2023), whereas open-ended exploration (Kidd, 2019; Loder, 2021; Pietroni, 2017) promotes personalised learning and increases users' sense of agency in navigating cultural information (Jin et al., 2022). Furthermore, incorporating first-person perspectives into broader historical narratives and employing human-voice narration reduces the psychological distance between users and cultural content, thereby fostering a more immersive, empathetic, and nuanced understanding of history and cultural diversity (Marshall et al., 2016; Oleksy & Wnuk, 2016). Similar findings in metaverse-based learning environments have shown that immersive narratives can enhance user memory retention and mitigate psychological distance in information spaces (Kim et al., 2025). During this process, a range of embodied-affective mechanisms emerge. These include users' behavioural self-awareness (Loonker et al., 2022; Nemcova et al., 2023), immersion (Lucifora et al., 2023), empathy (Shibasaki et al., 2017), emotional attachment (Jin et al., 2022; Kidd, 2019), memory linkage (Foglia & Wilson, 2013; Ma et al., 2023), and cultural identification (Chu et al., 2016; Loonker et al., 2022). Collectively, these mechanisms contribute to a deepened affective response and support the emergence of aesthetic appreciation grounded in embodied cultural experiences.

5.2.2. Cognitive development and meaning-making

Cognitive development and meaning-making constitute the second key dimensions of the decoding process in XR-based cultural heritage information spaces. On one level, embodied decoding supports users' knowledge acquisition and conceptual growth. Narratives in XR environments that integrate virtual and real-world embodied experiences enable users to build foundational cultural knowledge through immersive simulation, and subsequently deepen their understanding via continued reflection and application in real-life contexts (Ji et al., 2021; Nemcova et al., 2023). This phenomenon also highlights the unique role of emotional memory in decoding in XR-based cultural heritage spaces (Baumeister et al., 2017), which enhances the long-term retention of cultural content and increases users' openness to affective engagement with the meanings embedded in heritage information. On another level, personalised meaning construction highlights the user-centred nature of embodied decoding. In XR environments, users interact with cultural content through their own perceptual and experiential frameworks and begin to perceive themselves as active participants in the narrative (Duranti et al., 2024). Their bodily responses extend beyond basic cognitive tasks such as observation or control to facilitate deeper interpretive insights into cultural meaning. Based on their prior experiences, users develop personalised understandings of cultural heritage and its historical contexts (Nemcova et al., 2023), and in some cases, reinterpret—or metaphorically re-encode—historical events to form individualised cultural narratives (Ihde, 1990). This enhances engagement and promotes a sense of personal relevance and cultural self-positioning.

5.3. RQ2: transition and transformation between information encoding and decoding

Understanding the mechanisms underlying the encoding-decoding continuum—particularly the transitional and transformational roles of embodied interaction—is essential for evaluating human-computer interfaces that increasingly depend on multimodal, context-aware interaction. In XR-based cultural heritage information spaces, both the transitional and transformational move from encoding to decoding are mediated through a critical domain: the user interface (UI). As interaction technologies have evolved, user interfaces (UI) have progressed from batch interfaces (BI) and command line interfaces (CLI) to graphical user interfaces (GUI) (Hartson & Hix, 1989), culminating in natural user interfaces (NUIs) that allow users to engage with information systems through natural modalities such as speech, gesture, and movement. Consistent with Gibson's ecological view of perception (Gibson, 1966), this shift from tool-centric to user-centric design reflects a broader recognition: the body is not merely a subject within an interface, but an interface itself. By leveraging XR's narrative and visual affordances, the user's body thus functions as the primary locus for sensory input and interactive feedback, creating a space where perception, action, and interpretation converge to dynamically construct and reconstruct XR-based cultural heritage information spaces.

To further articulate this process, we distinguish between two interrelated dimensions:

(1) Transition, which refers to the sensorimotor and perceptual coupling between the user's body and the XR environment.
(2) Transformation, which captures the bidirectional flow characteristics of the process, from embodied translation to the construction and reconstruction of cultural meanings.

5.3.1. Transition: catena of body and environment

The creation of XR-based cultural heritage information spaces requires more than just identifying and organising the physical characteristics of heritage (i.e. object-centred affordances), as well as a shift towards a user-centred perspective that treats the body as a central interface component. Once perceptual engagement is initiated through encoding, the users' bodily actions enter a continuous, real-time interaction loop with the environment. This sensorimotor coupling serves as the primary mechanism that links encoding to decoding, illuminating how bodily engagement—through movement, perception, cognition, and social interaction—enables and sustains this transition (Myers et al., 2000).

The transition from encoding to decoding, first and foremost, requires the participation of digital and intelligent technologies. Artefacts, as key human-computer interfaces, function as components of the body's extended cognition (Clark & Chalmers, 1998). They provide a platform for interactive engagement in which the user's body functions as both a receiver and a processor of sensory information, enabling its encoding and subsequent decoding. The immersive features of XR technology, including spatial audio and haptic feedback, enhance a user's sense of presence within the virtual space. This heightened sense of presence is translated into cognitive outcomes through embodied actions, including movement, gaze tracking, and gesture selection, which facilitate a seamless transition from information input to personal interpretation. Moreover, to strengthen the connection between the user's body and environment, certain actions, such as reaching out to touch, simulating ancient crafts, or using traditional tools, can directly alter virtual objects, transform cultural scenes, and even influence the progression of historical narratives (Fu et al., 2020; Ji et al., 2021; Nemcova et al., 2023). These actions deepen immersive engagement with cultural content, act as critical links between the user's body and the external environment, and further facilitate the transition from encoding to decoding.

Users' understanding of their position within the environment, as well as their relationships with others, also plays a critical role in facilitating the coupling between the body and the environment (Weissenberger et al., 2018). In multi-user XR environments, users can engage in real-time collaboration, communication, and shared experiences within the same virtual space (Kenderdine et al., 2009; Lucifora et al., 2023). This form of collective participation deepens individual cognitive engagement and fosters the development of a shared cultural experience, which contributes to the transfer of cross-cultural knowledge and co-creation of value.

The effectiveness of the transition between information encoding and decoding is influenced by two key factors: the complexity of the interaction task and the adaptability of the body's physicality (Kim & Allen, 2002). While complex interactive tasks such as participatory performance and scenario simulation games are likely to stimulate a higher level of cognitive engagement, they also place greater demands on the user's physical control abilities and the responsiveness of the system. Therefore, as discussed in Section 5.1.1, encoding should calibrate task difficulty, interaction pace, and feedback mechanisms in line with the affordance principle of embodied cognition, thereby ensuring a balanced relationship between cognitive load and information expression. On the other hand, the core of the interaction process lies not only in how information is conveyed through actions but also in how these actions contribute to the construction of cognitive structures. The perspective of embodied cognition suggests that cognition is not merely a process of representing the world, but of actively constituting the world through embodied action (Varela et al., 2017). Every action performed by the user during embodied interaction in XR environments for cultural heritage—whether grasping, throwing, touching, walking, or listening—can be seen as a 'cognitive operation'. While there are universal cognitive patterns grounded in human bodily experiences, they are modulated by cultural particularities (Iyer, 2002). Only when these actions align with users' cognitive processes can the dynamic coupling between the body and external environment be fully realised.

5.3.2. Transformation: from embodied translation to the construction and reconstruction of cultural meaning

As shown in Fig. 5, the embodied encoding and decoding of cultural heritage in XR environments is not a static or opposing process but rather a dynamic, bidirectional flow that integrates embodied elements, the physical environment, and sociocultural contexts (Pietroni et al., 2012). This process reflects embodied translation and the construction, and even reconstruction, of cultural meaning, thus representing the transformation between encoding and decoding.

The transformation from encoding to decoding is most evident in a user's shift from passive observer and information recipient to co-producer of cultural meaning through embodied engagement, thereby dissolving the boundary between encoding and decoding (Russo et al., 2008). Therefore, information encoding is no longer a one-way transmission of symbols; it is an embodied translation process. Initially, symbolic cues are acquired from the physical and sociocultural environment and translated through digital techniques into interactive media content, body image, and body schema. Further, artefacts, characters, and embodied interactive behaviours serve as an 'action framework' to guide user participation, enhancing the intentionality of the experience and embedding cultural information into user actions. During this process, the body's sensory system functions as an interactive interface deeply embedded in the environment, transforming encoded information into interactive 'experiential events' that unfold through dynamic interactions and lay the groundwork for subsequent decoding.

A deeper transformation from encoding to decoding is reflected in the subsequent reconstruction of cultural meanings. The decoding process elicits and cultivates profound emotional responses, shaping the personal understanding of cultural meaning grounded in individual experiences. The transformation of 'code-information-meaning' is thus achieved. However, as highlighted by the perception-action loop in embodied cognition theory, action is not merely the result of perception but also serves as the starting point for new cognitive processes. In other words, decoding can influence encoding. The new insights that users generate through cultural experiences may be fed back into the narrative design, system updates, and re-encoding processes, thereby facilitating the reconstruction of cultural meaning. This discovery aligns with recent advances in digital humanities, where non-monotonic knowledge systems enable the dynamic reconstruction of meaning across iterative user interactions (Pineda et al., 2020). This approach not only extends Hall's concept of 'negotiated decoding' but also aligns with the embodied cognition theory's emphasis on the 'dynamic fluidity of cognition'. Consequently, the relationship between encoding and decoding evolves from a one-way transmission of information into a multidimensional interaction, fostering a richer and more nuanced sense of identity (Lakoff et al., 1999).

5.4. RQ3: the potential of embodied interaction as an interdisciplinary approach

Assessing the effects of the encoding and decoding of cultural heritage information in XR-based spaces requires an interdisciplinary approach. Current studies integrate various research objectives and application contexts using qualitative, quantitative, or mixed methods. These methods typically involve adaptation or modification of existing scales, and the observation dimensions include psychological, behavioural, and physiological measurements (Kawulich, 2005).

5.4.1. The dual-path evaluation framework

Both 'encoding performance' at the system level and 'decoding outcomes' at the user level need to be considered during evaluation. The evaluation tools and indicators used primarily focus on the user's actual interaction process in an XR environment for cultural heritage, addressing both embodied and non-embodied elements, although they remain fragmented in terms of evaluation focus and scope. Based on an understanding of embodied interaction, a dual-path evaluation framework (Fig. 6) was proposed to conduct a detailed analysis of the encoding and decoding effects of cultural heritage information from the system and embodiment dimensions. By integrating these two paths, we establish a unified evaluation logic that expands the applicability of embodied cognition theory to the measurement of embodied interaction in XR environments for cultural heritage and offers a clear and practical framework for future evaluation systems.

The first involves assessing the interaction effects of the information system and determining whether cultural heritage information is appropriately encoded and integrated into the XR environment. The XR environment is viewed here as an important human-computer interaction system that combines content, technology, and interaction. Additionally, the user's body is considered a component of this interaction system. This path allows for an analysis of whether the system effectively presents and supports the interaction of cultural information during the encoding phase from the perspectives of system performance, functional design, and user experience. The evaluation indicators centre on the users' basic perceptions of the system's operational performance, including the usability, ease of use, and effectiveness of the system functions, as well as the pleasure, expectation fulfilment, and satisfaction derived from the system's responses (Ji et al., 2023; Raheb et al., 2021; Zhang & Bryan-Kinns, 2022). For instance, in the QiaoLe VR system, usability was assessed through questionnaire items measuring users' perceived ease of use, fluency of interaction, and clarity of interface functions, while expectation fulfilment and enjoyment were measured through questions such as 'I met my expectations through this experience' and 'I would like to repeat the experience I just had' (Zhang & Bryan-Kinns, 2022). These indicators enable designers to evaluate whether a system's functional encoding of musical instrument heritage aligns with user requirements and interaction goals across different interaction modes.

The second path focuses on the effects of embodied interaction, emphasising whether users successfully translate encoded content

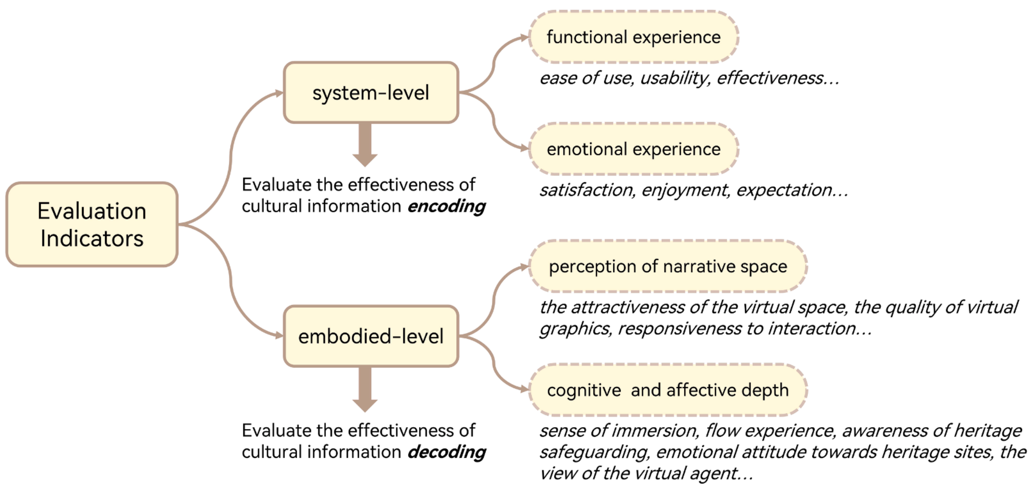

Fig. 6. Dual-path evaluation framework for embodied interaction in XR environments for cultural heritage.

into cognition, emotions, and meaning. Unlike technical performance evaluations at the information system level, assessments of embodied interaction focus on the coupling between the user's body, senses, and the external environment during the encoding-decoding process. These evaluations are typically based on behavioural experiments, and their scales or interview questions often reflect intertwined themes such as 'embodiment—empathy—silence' (Kidd, 2019). Many studies use pretest and posttest questionnaires to compare cognitive changes before and after interaction. The pre-test questionnaire examines users' prior knowledge, motivation, and relevant experience, whereas the post-test focuses on users' mastery of knowledge, system immersion, interaction smoothness, and related factors (Anastasovitis & Roumeliotis, 2018; Guo et al., 2024; Volkmar et al., 2018). In addition, to assess users' perceptual changes, the indicator system includes subjective feedback on factors such as the attractiveness of the virtual space, quality of virtual graphics, and responsiveness and adaptability of the visual feedback (Anastasovitis & Roumeliotis, 2018; Liu et al., 2022). To capture users' deeper decoding of cultural meaning, researchers have introduced additional emotional and cognitive indicators such as sense of immersion, flow experience, awareness of heritage preservation, emotional attitudes towards heritage sites, perceived meaning of multicultural heritage sites, self-reported learning effectiveness and motivation, and impressions of virtual agents (Guo et al., 2024; Jin et al., 2022; Oleksy & Wnuk, 2016). For example, in the Zen-based MR experience by Guo et al. (2024), researchers evaluated participants' perceived spiritual immersion, emotional resonance, and cultural understanding using a 5-point Likert questionnaire combined with post-session interviews, capturing responses like 'I gradually forgot myself and my surroundings'. Similarly, in Jin et al.'s (2022) study on traditional Chinese art, participants engaged with cultural scenes through VR and multi-touch tabletop interaction, and the post-test results showed increased motivation and personal meaning-making, as measured by shifts in heritage preservation awareness and reflective feedback. These indicators provide deeper insights into users' emotional resonance, value identification, and personal meaning-making.

5.4.2. The wide application and prominent impact of physiological measures

In the interconnected physical and digital realms, embodied interactions heighten users' sensory perceptions and undergo significant changes in their physiological indicators, potentially altering the overall quality of the experience (Russell, 2003). Physiological measures, a key means of capturing dynamic user responses, are increasingly being applied to evaluate the effects of embodied interaction in XR-based cultural heritage environments. The tools used include EEG (Ren et al., 2024), GSR (Wen et al., 2021), EMG (Funk et al., 2024), fNIRS (Su et al., 2023), fMRI (Moll et al., 2005), Eye Tracking (Shi et al., 2023), emotional processing algorithms, and other technologies. By designing embodied interaction tasks, these inputs are transformed into commands through gestures, voices, facial expressions, head movements, or combinations of these elements, enabling the collection of users' physiological data for deeper analysis (Capece et al., 2024). Given the synchronisation between virtual and real body movements, these physiological data provide a foundation for understanding the users' sense of ownership and agency, which helps clarify their priorities, preferences, and underlying intentions within their information needs. This can mitigate representation errors caused by human visual perception characteristics (Rensink et al., 1997) or the tendency of subjects to rationalise their behaviour (Nisbett & Wilson, 1977). Ultimately, these results will deepen our understanding of the nature, role, and characteristics of information behaviour in XR environments, enabling a more effective design and configuration of cultural heritage information spaces.

Importantly, because user physiological responses and emotional fluctuations are key components of information transmission, physiological measures further influence the encoding and decoding processes of information. Physiological monitoring and analysis can influence the content designed in the encoding phase. Biopsychological response, an index of empathic involvement, reflects user groups' points of interest, emotional reactions, and cognitive load in relation to different elements within XR-based cultural heritage information spaces. This provides a data-driven foundation for refining encoding strategies, integrating cultural information into embodied interaction to better meet user needs, and accumulating valuable experiences to achieve more universal cultural heritage information encoding in the future. On the other hand, physiological monitoring and analysis also alter users' perception in the decoding phase. Physiological data enable the avatar to mirror the user's body, allowing users to control the avatar's real-time feedback through gestures and postures, which can even influence the environment and storyline, giving users a profound sense of 'becoming part of the storytelling'. During decoding, this deep interaction—driven by physiological data—blurs the boundary between immersion and reality, enhances users' capacity to explore history and other cultures, and fosters empathy, which enables a more profound connection with the past (Genc & Häkkilä, 2021).

Embodied interaction in XR environments for cultural heritage has evolved from a process of information transmission to a dynamic experience encompassing emotional resonance, cognitive interconnection, and identity reconstruction. The collection and integration of diverse data offer researchers multiple methods for evaluating individuals and groups, thereby expanding the analyses of the relationship between embodiment and information behaviour. In the future, the latest developments in interdisciplinary fields such as psychology, neuroscience, computer science, and cultural heritage studies will increasingly be incorporated into the development of evaluation methods and criteria, offering researchers more profound insights into embodied interaction in XR environments for cultural heritage.

6. Conclusion

6.1. Theoretical implications

This study enhances the theoretical understanding by integrating embodied cognition with Hall's encoding/decoding model to explain how meaning is constructed in XR-based cultural heritage contexts. Unlike traditional applications of Hall's model that focus on symbolic media, our framework positions the human body as an active interface in both the encoding and decoding processes. This new perspective bridges cognitive theory with sociotechnical interaction and expands the existing evaluation framework for XR interactive interfaces (Pei et al., 2023). While traditional reading or art appreciation interactions also mediate experiences through the body, they typically recruit a narrower set of senses, predominantly visual and kinesthetic feedback from simple sliding gestures (Ito et al., 2014; Latini et al., 2020). Our paradigm inherits the physical and sociocultural elements highlighted in prior work and, crucially, foregrounds under-emphasised body channels such as physiological signals arising from the cardiorespiratory system, skin, and brain. Consequently, the framework not only explicates encoding and decoding in XR-based cultural heritage information spaces, but also accounts for the same mechanisms in conventional settings, offering a deeper interpretation of the roles played by often-overlooked embodied elements.

Compared to recent embodied cognition models applied to cultural heritage (Chen et al., 2025; Hu et al., 2025; Zhang & Xu, 2024), our approach extends beyond conceptual categorisation by integrating embodied elements into a unified encoding-decoding paradigm. While prior studies underscored symbolic engagement in early design and experience segmentation in mid-term interaction, our model systematically traces how embodied interactions evolve into emotional resonance, cognitive integration, and cultural meaning-making through dynamic information flows. This allows us to operationalise cognitive-affective learning and experience-based cultural transmission within a coherent evaluation framework. By situating the human body as both an interface and processor and aligning embodied experience with the information encoding-decoding process, this framework offers a scalable mechanism for analysing embodied information behaviour in immersive, multisensory XR-based environments, extending embodied cognition theory from interpretive to interactive, spatially grounded domains.

Our model also contributes to embodied information behaviour research, which has highlighted the bodily basis of information practices, but lacks structured models for immersive contexts (Polkinghorne, 2023; Zhong et al., 2023). The 22 components identified across five dimensions provide a conceptual foundation for analysing how sensory, affective, and cultural cues shape embodied information behaviours in XR environments.

Moreover, we respond to calls for dynamic conceptions of information spaces (Lueg, 2015), situating information as enacted and reinterpreted through real-time interaction. This aligns with ecological and situated cognition perspectives (Dourish, 2001; Glenberg, 1997b) and extends cultural heritage informatics by embedding meaning-making in the embodied experience.

6.2. Practical implications

Compared with prior studies that proposed replicable models applying embodied cognition in digital heritage experiences, such as AI-driven embodied interactive systems for opera preservation (Yang et al., 2025), multisensory experience interaction design application strategies (Lin & Lu, 2024), and tangible smart replicas to encourage physical engagement (Duranti et al., 2024), our model does not stop at the interface or object level. It provides a system-level framework for embodied interaction that supports end-to-end reasoning from information encoding to decoding. These structured paths bridge experience design and embodied evaluation, enabling upstream users, including XR system designers, museum professionals, and cultural content developers, to deploy embodied elements and assess their interpretive and affective effects. The proposed framework supports the structured integration of cultural heritage information into embodied environments and enhances the engagement and interpretability of downstream users. In practice, the dual-path evaluation framework proposed in this paper applies not only to XR environments, but also—at least in part—to user-experience assessment in low-resource or non-immersive settings. Regarding metrics, the system-level evaluation draws on measures established in traditional (non-XR) immersive contexts to examine whether the arrangement of information elements and interaction modalities aligns with human sensory characteristics. Methodologically, HCI studies in non-immersive environments have employed physiological measures (Chen et al., 2024; Kühnapfel et al., 2024). Additionally, the framework is extensible. It can be combined with other scales and instruments, and users can select the appropriate dimensions and specific indicators for targeted assessment. These properties expand the applicability of the framework and help address equity concerns regarding cultural heritage dissemination.

The proposed model also directly responds to the challenges raised in intangible cultural heritage (ICH) digitisation research (Hou et al., 2022), which has stressed the difficulty of capturing ephemeral embodied practices such as folk performances, rituals, and oral transmission. By structuring the evaluation around both system- and user-level outcomes, our dual-path framework provides a means of measuring whether ICH elements have been effectively externalised, preserved, and perceived, particularly when symbolic forms are insufficient. For instance, while projects such as i-Treasures or Terpsichore highlight new forms of ICH representation, they often lack integrated frameworks to trace how users emotionally and cognitively decode the embodied knowledge they encounter. Thus, our model offers a more complete solution for designing and evaluating ICH-specific systems, and corroborates previous findings from user experiments on embodied interaction, highlighting the interactive effects of informational and emotional support on human cognition (Wang et al., 2025; Pala et al., 2025).

Finally, our model is relevant to cultural education and tourism. Transforming the body from generalised parameters to precise parameters can inform the analysis of users' decision-making orientation towards cultural information and offer real-time feedback for adaptive system optimisation, thereby enhancing personalisation and long-term user engagement in educational and tourism-oriented XR applications.

6.3. Limitations and future work

Although this study provides a conceptual framework based on a comprehensive synthesis of prior empirical research, it is essentially a qualitative, theory-building meta-synthesis. The work therefore lacks direct user studies, physiological measurements, and interaction analyses, which constitute a significant limitation of the present research. Although empirical validation is beyond the scope of this conceptual study, the framework provides a structured basis for the future experimental testing and implementation of the system. Future research will focus on developing XR prototypes and applying user-centred design methods, including usability testing, cognitive walkthroughs, and physiological monitoring, to empirically validate the proposed encoding-decoding model and evaluation framework. Integrating real-time user feedback will also enable iterative refinement and expanded the applicability of the framework across diverse cultural heritage scenarios.

In addition, the dual-path evaluation framework proposed in this study has certain limitations. First, it sets a relatively high technical requirement—for example, it requires physiological monitoring equipment. Second, the framework is intended as a general-purpose assessment of the encoding and decoding effects within XR-based cultural heritage information spaces and does not incorporate other potential influences. In practice, they may need to be augmented with contextual factors that can shape the decoding outcomes, including users' prior knowledge, digital literacy, and experiences with XR technologies.

In conclusion, as a meta-synthesis, this study is not suitable for quantitative performance comparisons with computational models such as large language models (LLMs). Future research should explore how LLMs and other AI-based generative models can be incorporated into XR environments for cultural heritage to simulate dynamic narrative agents, generate context-aware cultural dialogues, and assist in the automated evaluation of user interactions, thereby extending the current framework.

CRediT authorship contribution statement

Xiaoguang Wang: Writing – review & editing, Funding acquisition, Conceptualization. **Jingyi Fu:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. **Sipeng Luo:** Writing – original draft, Formal analysis, Data curation. **Ke Zhao:** Writing – original draft, Conceptualization. **Qingyu Duan:** Writing – review & editing, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Data availability

Data will be made available on request.

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