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Identifying key factors influencing immersive experiences in virtual reality enhanced museums

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This study investigates how virtual reality (VR) technology shapes immersive experiences in museum environments. It aims to identify the critical factors that determine the quality and effectiveness of immersion and to explore whether overlooked peripheral elements—beyond core constructs such as the Technology Acceptance Model (TAM)—significantly influence user experience. To address these questions, a multi-dimensional, hierarchical indicator framework was developed, encompassing technical, behavioral, and cultural dimensions. The Analytic Hierarchy Process (AHP) was employed to analyze weighted evaluations from expert panels in China and South Korea.The results indicate that core technical indicators—such as Perceived Usefulness and Perceived Ease of Use—received the highest weights, reaffirming the explanatory power of TAM in VR-based museum applications. Meanwhile, peripheral indicators—including Interactivity, Atmosphere Building, Regional Characteristics, and Authority—played a moderating role in enhancing user engagement, contextual coherence, and trust. These findings reveal deeper psychological and cultural drivers of immersive experiences. Accordingly, this study proposes a conceptual framework that moves beyond technological determinism by integrating user motivation and cultural context, offering both theoretical insight and practical guidance for optimizing VR exhibition design in museums undergoing digital transformation.

Keywords Virtual reality, Museum, Immersive experience, Analytic hierarchy process (AHP), Technology acceptance model (TAM), Cultural context

With the increasing adoption of virtual reality (VR) technology in cultural institutions, immersive experience has become a key focus in museum research and practice. VR provides visitors with perceptual and interactive pathways that transcend traditional exhibition formats by leveraging graphical rendering, multimodal interaction, and spatial reconstruction. Driven by the emerging concept of the “audience-centered museum,” museums are evolving into platforms for cultural participation and identity construction[1]. VR, in particular, offers unique advantages for engaging “digital natives”—a technologically adaptive, youth-oriented user group[2]. noted, VR enhances cultural engagement and learning motivation among younger audiences due to their higher levels of technological fluency and sensitivity to interaction.

Despite VR’s potential to enrich immersive experiences, museums face numerous implementation challenges. Most VR programs are curated primarily from expert perspectives and often lack systematic attention to user behavior and emotional responses. Moreover, the integration of VR in public museum spaces raises practical concerns such as device security, spatial constraints, and sensory overload[3]. observed, in the absence of effective guidance and spatial design, immersive systems may cause behavioral disruptions, perceptual dissonance, or even safety risks.

More importantly, current research often emphasizes surface-level variables—such as system performance and technology acceptance—while overlooking deeper user motivations and psychological mechanisms[4]. Although models like the Technology Acceptance Model (TAM) and the Information System Success Model (ISSM) are widely used in VR research, relatively few studies examine emotional drivers, cultural identification, or geographical contextualization.

This study addresses two core research questions:

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RQ1: In the context of VR-enhanced museums, what are the key factors determining the quality and effectiveness of immersive experiences? How are these factors translated into user satisfaction through perceived motivation?

RQ2: Beyond core indicators like Perceived Usefulness and Perceived Ease of Use, are there underexplored peripheral indicators that significantly influence user experience? Do these indicators reflect implicit or unmet user needs?

To answer these questions, this study focuses on VR-enhanced physical natural history museums, drawing on expert evaluations from 15 domain specialists in China and South Korea. A hierarchical indicator system was constructed to model the variables affecting immersive experience, with the Analytic Hierarchy Process (AHP) employed as the primary methodology. AHP is particularly suited for small-sample, multi-level modeling and enables the quantification of expert judgments, making it preferable to regression analysis or entropy-based methods in this context.

The study adopts TAM and ISSM as its theoretical foundation, while also incorporating extended frameworks such as Long Tail Theory, Participatory Design, Edutainment, and Regional Coordination. These additions allow for the development of a multi-layered structure that encompasses both core and peripheral indicators.

Given generational differences in perception, this study targets "digital natives"—young museum visitors with high technological adaptability and strong expectations for interactivity. This focus enhances both the clarity and practical relevance of the model. Rather than merely reaffirming TAM, this study seeks to uncover and integrate less-explored pathways of influence—creating an evaluation framework that bridges technological functionality, user motivation, and cultural context. Ultimately, the research provides both theoretical contributions and practical guidance for optimizing immersive VR exhibitions in museums undergoing digital transformation.

Literature review

Virtual reality technology and museum experience

As VR technology advances, its application in museums is transforming traditional exhibition formats and enhancing visitor engagement, interactivity, and satisfaction[5–7]. Scholars have evaluated VR-based immersive experiences through various theoretical perspectives. For example[8],, using experience economy theory, confirmed that VR enhances both immersion and memory retention[9]. developed a 3D digital exhibition of historical costumes, highlighting how immersive interaction facilitates cultural dissemination. Generational differences also influence reception[10]: reported that younger users respond more positively to virtual exhibitions, a finding supported by other studies[11–13] showing higher levels of immersion among younger audiences. Collectively, these studies underscore VR's potential to deepen museum experiences while revealing the complex mechanisms that shape user engagement. They point to the necessity of systematically identifying key influencing variables and understanding their interrelationships.

Application and limitations of the technology acceptance model

The Technology Acceptance Model (TAM), proposed by[14], remains one of the most widely applied frameworks for studying immersive VR experiences. At its core, TAM posits that Perceived Usefulness and Perceived Ease of Use determine users' behavioral intentions to adopt technology. Over time, TAM has been extended in multiple directions[15]: integrated TAM with the Information System Success Model (ISSM) and immersion theory to explore how system quality mediates VR acceptance[16]. introduced cognitive dimensions such as Perceived Playfulness and Perceived Convenience[17]. incorporated external variables such as visual aesthetics and technological readiness to enhance cultural adaptability[18]. introduced constructs including user satisfaction and social mimicry to highlight the importance of social feedback in digital environments.

A review shows that about 38.9% of VR-related museum studies since 2010 have adopted TAM or its variants[17]. However, its limitations are increasingly noted. For instance[19], argued that TAM overlooks user diversity in age or digital literacy[20]. emphasized its inadequacy in addressing intergenerational gaps[7]. found that prior familiarity with museums significantly impacts VR adoption, which is not captured in TAM. In the context of immersive museum applications, three theoretical gaps are particularly evident:

1. Overemphasis on Technical Factors: Existing models underrepresent museums' educational and cultural roles.
2. Neglect of Spatial and Cultural Context: Regional identity and spatial storytelling—key to museum immersion—are often overlooked.
3. Lack of Generational Sensitivity: TAM fails to account for older users' cognitive and operational barriers.

Theoretical integration and indicator expansion

To improve the explanatory power and adaptability of immersive experience models, recent scholarship has moved toward multi-theoretical integration. A notable contribution is the Long Tail Theory, which provides a framework for identifying peripheral variables that may exert significant influence within specific user groups or cultural settings. Factors such as operability tolerance, future orientation, and knowledge asymmetry — often overlooked in mainstream models — can significantly impact immersive engagement for adolescents, older users, or non-mainstream cultural audiences. Thus, evaluation systems should account for the dynamic weighting and contextual relevance of such micro-variables in relation to core indicators.

As user expectations shift from functional satisfaction to emotional engagement and cultural alignment, theories like Participatory Design and Affective Computing are gaining prominence in the development of digital exhibitions[21]. emphasized that the immersive impact of digital cultural products depends heavily on emotional arousal and cultural resonance. In VR-based museum contexts, this highlights the importance of incorporating indicators such as Cultural Relevance and Emotional Guidance, which can guide users from sensory participation toward deeper identity construction—ultimately enhancing motivation and cultural memory formation.

Constructing the evaluation indicator system

Theoretical foundation

In constructing the evaluation framework for immersive experiences, this study synthesizes theoretical insights from technology acceptance, information system success, and cultural communication. This section outlines how these foundational theories inform the structure and definition of each indicator dimension within the proposed model.

First, the Technology Acceptance Model (TAM), proposed by[14], posits that Perceived Usefulness and Perceived Ease of Use are core variables influencing users' adoption of new technologies[22]. further emphasized that cognitive efficiency and task support afforded by technology are key drivers of user motivation. In the context of VR-enhanced museum environments, this dimension captures whether users perceive the VR system as helpful in understanding artifacts, improving viewing efficiency, and enhancing learning outcomes. Accordingly, this study includes Memory Retention and Self-Efficacy under Perceived Usefulness to reflect the cognitive and emotional value VR contributes[23]. also highlighted that interface friendliness and smooth interaction are strong predictors of continued engagement with information systems. In line with this, indicators such as Operability, Compatibility, and Adaptability are employed to assess system usability across diverse cognitive profiles, with particular attention to interaction thresholds and learning costs. Additionally, Personalization is introduced as a complementary sub-indicator to evaluate the system's responsiveness to user-specific needs, especially for technology-sensitive younger audiences.

Second, the Information System Success Model (ISSM), revised by[24], emphasizes the interplay among System Quality, Information Quality, and Service Quality in evaluating information systems. This model is increasingly relevant for assessing digital cultural display systems, particularly in measuring the timeliness, accuracy, intelligibility, and contextual coherence of information delivery. In this study, Authority, Completeness, and Timeliness are classified under Information Quality to gauge users' perceptions of content credibility, update speed, and semantic cohesion in VR exhibitions. System Quality pertains to the technical performance of the system, including response time, operational stability, and platform compatibility[20]. In immersive environments, latency or technical disruptions can significantly break the sense of flow and emotional investment. To capture this, Stability, Security, and Maintainability are included to evaluate system reliability and technical accessibility.

The concept of Edutainment emphasizes the integration of educational value and entertainment to foster learning motivation and emotional engagement[25,26]. argued that museums should employ contextualized content design and interactive mechanisms to stimulate cognitive involvement and exploratory behavior. This view aligns with immersion theory as articulated by Slater, which highlights "sensory realism" and a sense of "presence" as essential components of deep immersion. Based on this convergence, the initial framework incorporates Enjoyment and Interactivity as secondary indicators under Edutainment, and links them to Educational Value to comprehensively reflect the relationship between visual perception, behavioral interaction, and learning outcomes.

Regional Coordination, in this study, refers to the alignment between VR exhibition content and the cultural context of the museum's geographic location, as well as the effectiveness of its digital representation and reconstruction[1]. noted that contemporary museums function not only as repositories of artifacts and knowledge, but also as social spaces for identity construction and cultural negotiation. This view echoes[27] assertion that museums should serve three concurrent functions: spatial storytelling, cultural reconstruction, and place-based perception. In VR exhibitions, a lack of contextual guidance can result in a sense of "cultural dislocation" or "cognitive disconnect." A clear mapping between virtual content and its cultural roots enhances users' sense of immersion, locality, and historical relevance[28].

Moreover, Regional Coordination carries significant cross-cultural value in a globalized context. Digital representations of regional culture not only promote local identity but also foster intercultural understanding and dialogue among global audiences[29]. As such, Regional Coordination should be viewed as both a local and global indicator, contributing to the cultural intelligibility and transmissibility of exhibition content. To reflect this, the framework includes three secondary indicators: Regional Characteristics (the extent to which local cultural features are represented), Atmosphere Building (fidelity of virtual settings to historical or geographic reality), and Foresight (potential for future development and digital heritage reuse). These indicators extend the cultural depth and societal relevance of immersive museum experiences.

Construction of the initial evaluation framework

Drawing on the theoretical foundations outlined above—including TAM, ISSM, Participatory Design, Edutainment, and Regional Cultural Identity—this study developed a preliminary evaluation framework consisting of six Primary Indicators and twenty-three Secondary Indicators (see Table 1). The framework covers core dimensions such as technological perception, information delivery, user interaction, and cultural adaptation, aiming to comprehensively assess immersive quality in VR-enhanced museum environments.

To ensure both scientific rigor and practical feasibility, the Analytic Hierarchy Process (AHP) was employed to determine the relative weights of each indicator. A panel of 15 experts from relevant academic and professional domains was invited to participate in the evaluation process. The questionnaire used the standard 1–9 AHP scale (with intermediate values 2, 4, 6, 8 and their reciprocals), and experts performed pairwise comparisons at both the primary and secondary levels. Each item was structured as a closed-ended comparative judgment, supported by clear instructions and examples to ensure consistency. All comparison matrices were tested for consistency ratios to validate the reliability and logical coherence of the weighting process.

15,638	15,638	15,638
Perceived Usefulness	Viewing Interest	The degree to which VR technology stimulates visitors' willingness to actively explore the museum.
Perceived Usefulness	Memory Retention	The extent to which immersive experiences enhance visitors' retention of exhibition content.
Perceived Usefulness	Self-Efficacy	Enhancement of visitors' confidence in immersive learning of historical and cultural content.
Perceived Usefulness	Cultural Relevance	Visitors' perceived alignment of exhibits with their own cultural background.
Perceived Ease of Use	Operability	The clarity and intuitiveness of the VR system's user interface.
Perceived Ease of Use	Adaptability	The system's ability to accommodate users across various age groups.
Perceived Ease of Use	Compatibility	Cross-platform consistency ensured through multi-device compatibility.
Perceived Ease of Use	Personalization	Customization of immersive content based on individual user needs.
Perceived Ease of Use	Interface Friendliness	The ease with which visual elements such as icons and text are understood.
Information Quality	Relevance	The degree to which immersive content aligns with the exhibition's theme.
Information Quality	Completeness	The comprehensiveness and systematic reconstruction of historical information.
Information Quality	Authority	The verifiability and accuracy of information sources.
Information Quality	Timeliness	The frequency and timeliness of content updates.
System Quality	Stability	The system's capacity to minimize operational failure rates.
System Quality	Security	Mechanisms for protecting user privacy and data security.
System Quality	Maintainability	The efficiency of system recovery from failures.
Edutainment	Educational Value	The effectiveness of conveying knowledge naturally within entertaining experiences.
Edutainment	Interactivity	The degree to which interactive experiences enhance engagement and novelty.
Edutainment	Plasticity	Flexibility in adjusting display formats or interaction modes.
Edutainment	Enjoyment	The intensity of enjoyment during the experience
Regional Coordination	Regional Characteristics	Accuracy in representing local cultural elements.
Regional Coordination	Atmosphere Building	The synergy between ambient atmosphere and exhibition themes.
Regional Coordination	Foresight	The practical significance of simulating future regional scenarios.

Table 1. Initial evaluation indicator Framework.

Attribute	Description
Total Experts	15 experts affiliated with institutions in China and South Korea
Institution Type	10 from academic institutions, 5 from museums, research institutes, or industry
Disciplinary Fields	Digital media, cultural heritage, user experience, HCI, immersive tech
Interdisciplinary Background	Combined expertise in design, communication, education, and digital content
Professional Experience	5 to 20 years; average of approximately 9.3 years
Regional Distribution	Institutions located in Yangtze Delta, Pearl River Delta, and Seoul area

Table 2. Summary profile of the expert panel ($N = 15$).

This study adhered strictly to the ethical standards of the Declaration of Helsinki. All participating experts were fully informed of the study's aims, data handling procedures, and their right to withdraw at any time. Informed consent was obtained prior to questionnaire distribution. At the same time, this study has been formally approved by the Research Office of Anhui University of Finance and Economics.

Expert feedback and indicator refinement

Given the methodological rigor required by AHP in structuring variable relationships and theoretical weights, this study prioritized the selection of experts with strong academic credentials and practical experience in digital culture integration. The final panel consisted of 15 interdisciplinary experts from China and South Korea, including 10 university-based researchers (professors, associate professors, and PhD scholars) and 5 senior researchers from non-academic institutions.

These experts were affiliated with 11 institutions—six in China and five in South Korea—specializing in areas such as digital media design, cultural heritage communication, and user experience. All participants had substantial experience in cultural-technology integration, including leading national-level digital heritage projects, developing VR-based museum navigation systems, and publishing in digital exhibition and interaction design. The panel was geographically distributed across East Asia's cultural and innovation hubs, including China's Yangtze River Delta and Pearl River Delta regions and the Seoul metropolitan area in South Korea. This ensured that the final evaluation framework was both theoretically robust and culturally representative. A summary of the expert panel's composition is provided in Table 2.

Before performing the AHP-based weighting analysis, a two-round Delphi method was used to establish consensus and refine the structure of the initial indicator system. In Round 1, experts rated each indicator's importance using a five-point Likert scale. However, the results showed insufficient consensus—evidenced by high standard deviations and significant rating variability—on four secondary indicators: Cultural Relevance, Timeliness, Interface Friendliness, and Enjoyment.

Based on feedback, three major revisions were made in Round 2:

1.Elimination of Theoretically Redundant Indicators:

Cultural Relevance was removed due to conceptual overlap with Relevance under Information Quality. Timeliness was excluded because of its limited applicability to relatively static museum content update cycles.

2.Consolidation of Overlapping Indicators:

Interface Friendliness was merged with Operability, referencing ISO standards in human-computer interaction that treat visual intuitiveness as a component of interface usability. Enjoyment was merged with Interactivity, based on flow theory, which suggests that user enjoyment arises from sustained engagement; conceptually, this indicator also overlapped with Viewing Interest.

3.Retention of Conceptually Adjacent but Operationally Distinct Indicators:

In addition to merging and eliminating overlapping indicators, experts also examined the conceptual proximity of Interactivity, Operability, and Plasticity. While initial concerns were raised regarding potential overlap, the panel concluded that each captures a distinct operational dimension: Interactivity emphasizes reciprocal feedback between users and content; Operability refers to the intuitiveness and fluency of the operational process; and Plasticity reflects the system's ability to adapt to diverse user needs and usage contexts. Based on this input, all three were retained as independent constructs in the final framework.

As a result of these revisions, the final evaluation framework consists of six Primary Indicators and nineteen Secondary Indicators(see Table 3).

Calculation and ranking of indicator weights

Weight calculation

Using the data provided by Expert 1 as an example, the square root method was applied to calculate the weights of indicators at each hierarchical level. The process began with computing the product of all elements in each row of the pairwise comparison matrix for the primary indicators. Then, the n-th root of each product was taken to obtain the geometric mean M_i. This process is illustrated in Eq. (1), and the results are shown below:

$$M_i = \left(\prod_{j=1}^{n} a_{ij} \right)^{\frac{1}{n}} \text{(i, j = 1, 2, … n) 1.}$$

M_1=(1*7*9*3*1/3*5)1/6 ≈ 2.6085 M_2=(1/7*1*2*1/5*1/9*1/3)1/6 ≈ 0.3583.
M_3=(1/9*1/2*1*1/5*1/9*1/3)1/6 ≈ 0.2727 M_4=(1/3*5*5*1*1/5*3)1/6 ≈ 1.3077.
M_5=(3*9*9*5*1*7)1/6 ≈ 4.5180 M_6=(1/5*3*3*1/3*1/7*1)1/6 ≈ 0.6640.

Next, the geometric means were normalized to derive the weight vector , as shown in Eq. (2):

$$W_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \tag{2}$$

W_1 = 2.6085/9.7292 ≈ 0.2681 W_2 = 0.3583/9.7292 ≈ 0.0368.
W_3 = 0.2727/9.7292 ≈ 0.0280 W_4 = 1.3077/9.7292 ≈ 0.1344.

Primary indicator	Secondary indicator	Indicator description
Perceived Usefulness	Viewing Interest	The degree to which VR technology stimulates visitors' willingness to actively explore the museum.
	Memory Retention	The extent to which immersive experiences enhance visitors' retention of exhibition content.
	Self-Efficacy	Enhancement of visitors' confidence in immersive learning of historical and cultural content.
Perceived Ease of Use	Operability	The clarity and intuitiveness of the VR system's user interface.
	Adaptability	The system's ability to accommodate users across various age groups.
	Compatibility	Cross-platform consistency ensured through multi-device compatibility.
	Personalization	Customization of immersive content based on individual user needs.
Information Quality	Relevance	The degree to which immersive content aligns with the exhibition's theme.
	Completeness	The comprehensiveness and systematic reconstruction of historical information.
	Authority	The verifiability and accuracy of information sources.
System Quality	Stability	The system's capacity to minimize operational failure rates.
	Security	Mechanisms for protecting user privacy and data security.
	Maintainability	The efficiency of system recovery from failures.
Edutainment	Educational Value	The effectiveness of conveying knowledge naturally within entertaining experiences.
	Interactivity	The degree to which interactive experiences enhance engagement and novelty.
	Plasticity	Flexibility in adjusting display formats or interaction modes.
Regional Coordination	Regional Characteristics	Accuracy in representing local cultural elements.
	Atmosphere Building	The synergy between ambient atmosphere and exhibition themes.
	Foresight	The practical significance of simulating future regional scenarios.

Table 3. Final evaluation indicator framework.

$W_5 = 4.5180/9.7292 \approx 0.4644$ $W_6 = 0.6640/9.7292 \approx 0.0682$.

Subsequently, the maximum eigenvalue λmax was calculated using the weight vector , following Eq. (3):

$$\lambda\text{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{(AM)_i}{M_i} \tag{3}$$

$\lambda_{max} = 1/6(1.6775/0.2681 + 0.2324/0.0368 + 0.1775/0.0280 + 0.8457/0.1344+$.
$3.0022/0.4644 + 0.4276/0.0682) \approx 6.3201$.

Consistency check

The Consistency Index (CI) and Consistency Ratio (CR) are essential metrics for evaluating the logical consistency of pairwise comparison matrices in AHP. After determining the weight vector, it is necessary to confirm that the matrix satisfies AHP's consistency requirements.

The CI is calculated using Eq. (4):

$$CI = \frac{\lambda\text{max} - n}{n - 1} \tag{4}$$

$CI = (6.3201\text{-}6)/(6-1) \approx 0.0640$.

To assess the CR, the Random Index (RI)—derived from established AHP reference values—was used (see Table 4). The CR is then computed as:

$$CR = \frac{CI}{RI} \tag{5}$$

$CR = CI/RI = 0.0640/1.24 \approx 0.0516$.

According to AHP standards, if $CR < 0.10$, the matrix is considered to be acceptably consistent. If $CR \geq 0.10$, expert feedback should be sought, and corresponding questionnaire responses must be revised before recalculating.

In this study, the CR value for the primary indicator matrix from Expert 1 was approximately 0.0516, satisfying the consistency criterion ($CR < 0.10$). Thus, the matrix was deemed logically consistent. The same procedure was followed for all other experts and indicator matrices.

Indicator ranking

To determine the composite weight of each secondary indicator, its local weight (from the pairwise comparison) was multiplied by the weight of its corresponding primary indicator.

After calculating the composite weights, all indicators were ranked to reflect their overall importance in the evaluation framework. These rankings provide insight into which dimensions exert the greatest influence on immersive VR experiences in museums.

The final results—including the comprehensive weightings and rankings for each indicator—are shown in Table 5; Fig. 1.

Consistency and sensitivity analysis of AHP results

To evaluate the relative importance of the six primary indicators, a pairwise comparison matrix was constructed based on expert judgments. Using the geometric mean method to aggregate individual inputs, the group-level comparison matrix was derived and normalized to compute the weights(see Table 6). The resulting eigenvalue (λ_{max}) was 6.530, and the Consistency Ratio (CR) was calculated to be 0.086, which is below the standard threshold of 0.1. This indicates satisfactory logical consistency in expert evaluations.

To further examine the robustness of the AHP-derived rankings, a sensitivity analysis was conducted. Specifically, the judgment score between "Perceived Usefulness" and "Perceived Ease of Use" was increased by 10%. The recalculated weights showed negligible variation, and the ranking of all primary indicators remained unchanged(see Table 7). This confirms that the prioritization results are stable and resilient to minor perturbations in expert input.

Research conclusions and implications

Results analysis

This study employed the Analytic Hierarchy Process (AHP) to calculate the weights of six primary indicators and nineteen secondary indicators, aiming to identify key variables that drive users' sense of immersion while shaping their emotional engagement and cultural identification. The results reveal that Perceived Usefulness and Perceived Ease of Use carry the highest weights among the primary indicators, reaffirming the centrality of core constructs from the Technology Acceptance Model (TAM) in VR-enhanced museum contexts. However,

Rank *N*	3	4	5	6	7	8	9	10	11	12
RI value	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48

Table 4. Average random consistency index (RI) Values.

Primary indicator	Primary weight	Primary CR	Secondaryindicator	Secondary weight	Secondary CR	Composite weight	Overall rank
Perceived usefulness	0.2875	0.0079	Viewing interest	0.6361	0.0026	0.1829	1
	0.2875	0.0079	Memory retention	0.1919	0.0026	0.0552	6
	0.2875	0.0079	Self-efficacy	0.1720	0.0026	0.0495	9
Perceived ease of use	0.2130	0.0079	Operability	0.4665	0.0068	0.0993	2
	0.2130	0.0079	Adaptability	0.2811	0.0068	0.0599	5
	0.2130	0.0079	Compatibility	0.0829	0.0068	0.0176	17
	0.2130	0.0079	Personalization	0.1695	0.0068	0.0361	13
Information quality	0.1792	0.0079	Relevance	0.4375	0.0032	0.0784	3
	0.1792	0.0079	Completeness	0.2707	0.0032	0.0485	11
	0.1792	0.0079	Authority	0.2918	0.0032	0.0523	7
System quality	0.0957	0.0079	Stability	0.3310	0.0008	0.0317	14
	0.0957	0.0079	Security	0.5157	0.0008	0.0493	10
	0.0957	0.0079	Maintainability	0.1533	0.0008	0.0147	18
Edutainment	0.1688	0.0079	Educational value	0.2443	0.0006	0.0413	12
	0.1688	0.0079	Interactivity	0.4573	0.0006	0.0772	4
	0.1688	0.0079	Plasticity	0.2983	0.0006	0.0504	8
Regional coordination	0.0558	0.0079	Regional characteristics	0.3602	0.0031	0.0201	16
	0.0558	0.0079	Atmosphere building	0.4473	0.0031	0.0249	15
	0.0558	0.0079	Foresight	0.1925	0.0031	0.0107	19

Table 5. Final weights and rankings of evaluation Indicators.

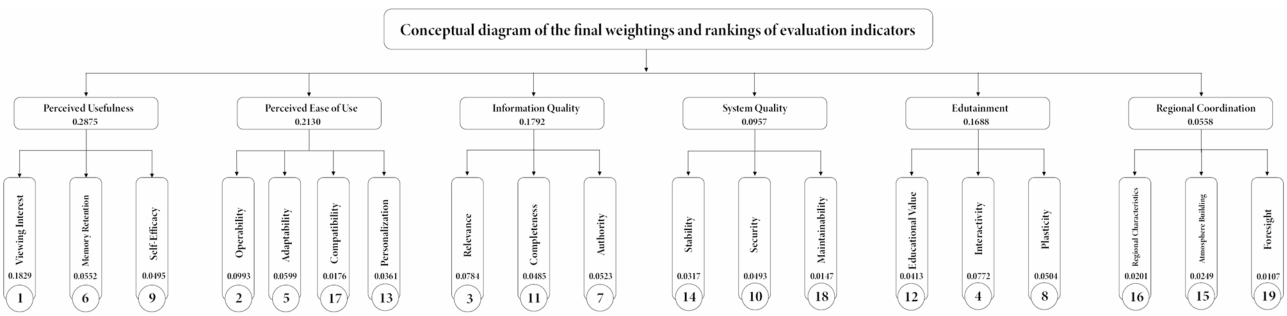

Fig. 1. Final Weights and Rankings of Evaluation Indicators.

Indicator	Example Pairwise Values	Normalized Weight	Final Weight	Rank
Perceived Usefulness	1.000	0.263	0.263	2
Perceived Ease of Use	7.000	0.040	0.040	5
Information Quality	9.000	0.029	0.029	6
System Quality	3.000	0.138	0.138	3
Edutainment	0.333	0.458	0.458	1
Regional Coordination	5.000	0.072	0.072	4

Table 6. Optimized primary indicator weight Calculation. $\lambda_{max} = 6.530$, CI = 0.106, CR = 0.086 < 0.1 → Consistency Pass.

immersive experience cannot be fully explained by "technical usability" alone. One of the most valuable contributions of this study lies not in reiterating the dominance of technical factors but in identifying a set of peripheral indicators with strong moderating potential—factors that significantly influence the psychological depth and cultural resonance of immersive experiences.

First, the high weights assigned to Operability and Interactivity indicate a paradigm shift in audience expectations—from passive, linear content consumption to dynamic, feedback-driven engagement. This aligns with Csikszentmihalyi's Flow Theory, which posits that deep immersive states emerge when task difficulty is appropriate, feedback is immediate, and emotional engagement is sustained. Within this framework, VR exhibition design must transcend static content delivery to establish a closed-loop system of interaction,

Indicator	Original Weight	Perturbed Weight (+10%)	Absolute Δ	% Change	Rank Change
Perceived Usefulness	0.263	0.266	0.003	1.26%	0
Perceived Ease of Use	0.040	0.039	−0.001	−1.55%	0
Information Quality	0.029	0.029	−0.000	−0.26%	0
System Quality	0.138	0.137	−0.001	−0.61%	0
Edutainment	0.458	0.457	−0.001	−0.28%	0
Regional Coordination	0.072	0.072	−0.001	−0.70%	0

Table 7. Sensitivity analysis results for primary Indicators.

emotional stimulation, and knowledge internalization. This is exemplified by projects like the Smithsonian Institution's Moonwalk VR, which integrates authentic NASA imagery, astronaut voiceovers, and interactive scenarios to transition users from "watching" to "participating." The project successfully fostered emotional engagement and cognitive involvement, demonstrating how Operability, Interactivity, and Educational Value can be holistically integrated into experiential design.

Second, although Atmosphere Building and Regional Characteristics—peripheral indicators under Regional Coordination—received lower overall weights, they highlight a critical mechanism of cultural contextual embedding. The essence of immersive museum experience lies not merely in the visualization of cultural symbols but in evoking a "sense of place" that reconstructs cultural belonging and identity within simulated environments. As[27] noted, cultural identification emerges through the dynamic coupling of space, symbolism, and memory—not simply from content novelty or volume. This form of "deep cultural embedding" modulates user motivation and enhances emotional resonance. For instance, the National Museum of Korea used VR to reconstruct Confucian educational spaces from the Joseon Dynasty, combining spatial and multisensory interaction to immerse visitors in traditional Confucian learning culture. This demonstrates how low-weight indicators, when thoughtfully designed, can significantly enhance cultural participation and immersive depth. Furthermore, the lower relative weight of regional indicators may reflect broader public tendencies to prioritize national historical narratives over localized cultural experiences—a pattern also observable in the differing popularity of national versus regional museums.

Finally, within the System Quality and Information Quality dimensions, although their total weight is lower than TAM-related indicators, sub-dimensions such as Authority and Security received notable expert attention. This underscores the foundational role of content credibility and system stability in cultivating user trust. Inaccuracies or technical failures—particularly in natural history contexts—can disrupt cognitive flow and diminish experiential coherence. Additionally, lower-weight indicators like Foresight and Plasticity should not be disregarded; their relatively modest weighting may reflect a broader design gap in supporting future-oriented thinking and sustainability scenarios in VR environments. According to Cognitive Load Theory[30], when users are not provided with structured guidance, they experience increased mental burden, which reduces their willingness to explore content deeply. Therefore, future immersive systems should incorporate nonlinear narrative structures that span past, present, and speculative futures. Such temporal cross-linking would enable users to construct more critical and extended cognitive frameworks.

Summary of core conclusions, the findings yield three key conclusions

4. Technical core indicators function as entry thresholds: Efficient operation and responsive systems are prerequisites for audience immersion.
5. Peripheral indicators serve as experiential regulators: Cultural and regional adaptability, interactive mechanisms, content flexibility, and cognitive alignment are essential for activating user engagement.
6. Immersion is shaped by dynamic, nonlinear mechanisms: Effective immersive exhibitions require integrated design across structural, contextual, and emotional dimensions—necessitating future refinements through cross-dimensional coordination.

Research implications

Enhancing multisensory guidance to stimulate viewing interest

Among the primary indicators, Perceived Usefulness and Perceived Ease of Use received the highest weights, reaffirming the relevance of TAM constructs in VR museum contexts. Specifically, Viewing Interest acts as a psychological entry point, motivating audiences to accept, understand, and actively engage with VR technology. According to the AIDA model (Attention–Interest–Desire–Action), immersion begins by capturing attention, sustaining interest, and converting it into action. Thus, VR exhibition design should emphasize multisensory coordination, integrating visual tension, auditory cues, and haptic feedback to establish a "perceptual guidance zone" during initial user interaction. For example, the VR Basilica Reconstruction project at France's Musée de Cluny used flickering candlelight, resonant chimes, and spatial audio to build emotional atmosphere—enhancing both user engagement and content retention.

Optimizing interaction processes to lower technical barriers

Operability emerged as the highest-weighted secondary indicator under Perceived Ease of Use, highlighting the importance of user-friendly design—especially for first-time or less tech-savvy visitors. While this study focused on digital natives, the importance of operability is likely even more critical for children, older adults, or individuals with low digital fluency. Museums should optimize interaction from both hardware and software perspectives. On the hardware side, gesture-based or voice-controlled interfaces with high compatibility and low learning curves are preferred. On the software side, interfaces should prioritize intuitive layouts, logical navigation, and default guidance modes to reduce cognitive load. Additionally, back-end systems should include monitoring protocols and automated diagnostics to ensure technical stability and minimize disruptions.

Establishing a dual trust mechanism: content credibility and technical security

User trust depends on both content authority and technical reliability. From a content perspective, source transparency, clarity, and narrative flow are essential. Overly academic language can hinder engagement. For example, the British Museum's Virtual Egyptian Tomb, developed with Google Arts & Culture, balanced scholarly accuracy with immersive storytelling using 3D modeling and guided narration. On the technical side, VR systems should implement safety protocols (e.g., fit detection, data minimization) to mitigate physical discomfort and privacy risks. High-traffic exhibitions should undergo stress testing and regular system maintenance. The Muséum national d'Histoire naturelle in Paris, for example, enforced session time limits and child monitoring features to promote safe and controlled VR use. Together, front-end design and back-end safeguards should be integrated into a cohesive trust framework that protects users while maintaining continuity.

Designing interaction-driven learning experiences

Within the Edutainment dimension, this study identified Interactivity and Plasticity as essential for immersive learning. Future exhibitions should follow an "interaction–feedback–knowledge construction" model, shifting from one-way information delivery to structured educational pathways. Layered learning modules—such as exploration tasks, contextual quizzes, or scenario-based role-playing—can deepen engagement and facilitate active participation. For instance, the Deutsches Museum in Munich developed a VR exhibit where visitors simulate historical engineering tasks with real-time feedback, enhancing empathy and knowledge acquisition. Complementary mechanisms like achievement badges, progress indicators, or virtual guides can help reduce cognitive load and sustain focus on learning objectives.

Embedding regional culture to deepen immersion

Immersive experience extends beyond technological sophistication—it involves activating cultural memory and spatial identity. While Regional Coordination was ranked lower overall, its contextual significance is especially salient in multicultural and local engagement settings. Incorporating regional cultural elements can enhance users' sense of belonging and emotional connection. Design strategies may include dialect voiceovers, reconstructed landmarks, and localized color palettes. For example, the Tamsui VR Reconstruction Project at the National Museum of History in Taipei used archival photos and audio recordings to recreate collective memory, fostering cultural resonance.

To build a dynamic feedback loop between design and experience, museums should deploy user evaluation mechanisms, including path tracking and post-visit surveys. Longitudinal tracking systems can be particularly useful for assessing adolescents' cognitive, emotional, and behavioral changes over repeated visits. Such data not only supports iterative design but also provides quantifiable metrics for evaluating the cultural communication efficacy of VR exhibitions.

Limitations and future directions

This study used AHP and expert evaluations to construct a comprehensive indicator system for assessing immersive experiences in VR museum environments. While the results yield theoretical insights and practical recommendations, several limitations must be acknowledged:

7. Cultural and Geographic Homogeneity: The 15 experts involved were primarily from China and South Korea, reflecting limited cultural diversity. Given that perceptual styles, interaction habits, and content preferences vary across cultural contexts, future research should recruit a more international panel, including experts from Europe, Southeast Asia, and North America, to enhance the model's cross-cultural validity.
8. Methodological Constraints of AHP: While AHP effectively reveals the hierarchical structure and relative importance of indicators, it does not capture interaction effects or dynamic contextual variables. Factors such as user age, digital literacy, or thematic preferences may significantly influence the salience of certain indicators. Future studies are encouraged to adopt complementary methods—such as Structural Equation Modeling (SEM) or multi-group comparative analysis—to explore moderation and mediation effects in the formation of immersive experiences.

In conclusion, VR-enhanced museum research is undergoing a shift from a technology-centered to a user-centered paradigm. Future development should be grounded in inclusive sampling and enriched by interdisciplinary frameworks. By integrating constructs such as cognitive load, cultural adaptability, and motivational design, researchers and practitioners can advance toward a holistic model—one that aligns experiential engagement with educational value and cultural communication.

Data availability

The data required for this paper is provided in the supplementary materials.

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Author contributions

This study was jointly completed by the following authors, with specific contributions as outlined below:• Ning Wang spearheaded literature review, research design, questionnaire development, data collection, manuscript drafting, and revisions.• Congcong Jia made substantial contributions to improving the CR value calculation of the expert judgement matrix and conducting sensitivity analysis to verify the robustness of the indicator ranking.• Jinling Wang provided critical support in topic selection, research framework design, data collection coordination, and research ethics approval, including expert liaison and substantive recommendations for data processing and manuscript refinement.• Zhimin Li directed data analysis and computational methodology optimization, while significantly enhancing scientific rigor and readability through multi-round manuscript revisions.All authors have made substantial contributions to the study and take full responsibility for the final version of the manuscript. Please note that this paper is a translated version of an original manuscript written in Chinese; we welcome any constructive feedback regarding potential linguistic imperfections.

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Declarations

Competing interests

The authors declare no competing interests.

Ethics approval

This study has obtained formal ethical approval from the Research Office of Anhui University of Finance and Economics.

Informed consent

Informed consent was obtained from all individual participants included in the study prior to their participation in the questionnaire. Participants were informed of the study's purpose, data usage, and their right to withdraw at any time.

Additional information

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