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Haptic feedback integration in virtual Huizhou architecture: Enhancing tactile perception of traditional craftsmanship

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Abstract

As virtual heritage exhibitions become increasingly prevalent, enhancing their sensory depth remains a critical challenge. This study investigates the potential of haptic technology to enhance virtual exhibitions of Huizhou architecture by simulating the tactile qualities of traditional architectural elements. Across experimental design incorporating user testing (n = 105 participants across three expertise groups), comparative analysis across three interface conditions (visual-only, visual-audio, and full multisensory), and ethnographic interviews with fifteen traditional craftsmen, this study explores how tactile simulation can bridge the sensory gap between physical and virtual heritage experiences. The research draws on embodied cognition theory and the phenomenology of perception to examine how haptic feedback influences visitors' understanding and appreciation of traditional craftsmanship in carved woodwork, stone textures, and brick patterns characteristic of Huizhou architectural style. Findings suggest that haptic integration significantly enhances user engagement (a mean increase of 1.4 points on a seven-point scale) and cultural comprehension (material identification accuracy improved by 34%), offering new pathways for immersive heritage preservation and education.

Keywords: Haptic feedback; Tactile simulation; Traditional craftsmanship; Embodied cognition; Sensory augmentation; Material culture preservation

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1. Introduction

Huizhou architecture, originating from the ancient Huizhou region in southeastern China (present-day Anhui province), represents one of China's most distinctive architectural traditions, characterized by its sophisticated wood carving, intricate stonework, and distinctive brick patterns (Wang *et al.*, 2020). These architectural elements embody centuries of accumulated craftsmanship knowledge, yet their preservation and transmission face significant challenges in the digital age (Lowenthal, 2015; Riegl, 1903). Traditional museum exhibitions and digital archives, while valuable for visual documentation, fail to capture the tactile dimensions that are fundamental to understanding the materiality and craftsmanship of these structures (W. Li & Zhang, 2021).

The integration of haptic feedback technology in virtual heritage experiences offers unprecedented opportunities to address this sensory limitation. Haptic technology, which enables users to receive tactile feedback through touch-sensitive interfaces, has evolved significantly in recent decades, moving from basic force-feedback systems to sophisticated multi-modal haptic displays capable of simulating complex material properties (Lederman & Klatzky, 2009; Stone, 2001). However, the application of haptic technology to cultural heritage preservation, particularly in traditional architecture, remains underexplored (Rahaman & Champion, 2019; Papagiannakis *et al.*, 2018).

McLuhan (1964) addressed the critical gap between visual-centric digital heritage preservation and the embodied, multisensory nature of architectural experience. By focusing on Huizhou architecture's distinctive tactile elements, we examine how haptic feedback can enhance virtual exhibitions and foster authentic, engaging cultural heritage experiences.

1.1. Research significance

The significance of our study extends beyond technological innovation to encompass cultural preservation, educational enhancement, and theoretical advancement in human-computer interaction (Ballantyne *et al.*, 2008). Traditional craftsmanship knowledge, particularly the tactile understanding of materials and techniques, is increasingly at risk of loss as master craftsmen age and traditional building practices decline (UNESCO, 2003). Haptic technology offers a novel approach to documenting and transmitting this embodied knowledge to future generations (Sylaiou *et al.*, 2018).

Furthermore, our study contributes to the growing field of cultural heritage informatics by proposing methodologies for capturing and reproducing the tactile qualities of architectural elements (Champion, 2011). The integration of phenomenological approaches with empirical user testing provides a comprehensive framework to evaluate the effectiveness of haptic simulations in cultural contexts. A synthesis of prior work and the remaining research gaps is presented in Table 1.

1.2. Critical analysis of previous research

Previous research has established the technical feasibility of haptic heritage applications and theoretical foundations for multisensory cultural experiences. However, three significant gaps remain: (i) A lack of material-specific haptic calibration for traditional architectural elements, (ii) the absence of expert craftsmen's validation in haptic system development, and (iii) limited empirical testing in East Asian cultural contexts. This study addresses all three gaps by systematically integrating psychophysical measurement, expert validation, and culturally grounded evaluation methodologies.

1.3. Research innovation and contributions

This investigation advances the field through five novel contributions:

i) Methodological innovation: Development of the first comprehensive framework integrating psychophysical calibration, expert craftsmen validation, and cross-

Table 1. Research background and critical analysis

Study	Focus area	Methodology	Key findings	Limitations	Gaps addressed by the present study
PURE FORM Project (Gherardini *et al.*, 2018)	Archeological artifact haptics	Experimental	Enhanced haptic exploration improved artifact understanding	Limited to small objects, no architectural focus	Extends to large-scale architectural elements
CHESS Project (Roussou *et al.*, 2015)	Personalized heritage experiences	Multi-modal framework	Improved visitor engagement through sensory integration	Generic framework lacking material-specific validation	Provides material-specific haptic calibration
DISCOVER Project (Tennent *et al.*, 2017)	Museum object haptics	User testing	Improved learning retention with haptic feedback	Western cultural contexts only	East Asian architectural heritage context
Sylaiou *et al.*, 2010	Virtual museum haptics	Experimental design	Presence and enjoyment correlate with haptic feedback	Visual-haptic only, no craftsmen validation	Incorporates expert craftsmen's evaluation
Stone, 2001	Haptic technology development	Technical review	Evolution from telepresence to VR haptics	No cultural heritage application	Applies advanced haptics to heritage preservation
Pallasmaa, 2005	Architectural phenomenology	Theoretical	Fundamental to architectural experience	Lacks empirical validation	Empirically tests phenomenological claims
Lederman & Klatzky, 2009	Tactile perception	Psychophysical	Identified key parameters for texture simulation	Generic materials, not traditional crafts	Applies to specific traditional materials
Y. Zhang, 2018	Huizhou architecture documentation	Cultural analysis	Material culture embedded in architectural elements	Visual documentation only	Adds a tactile dimension to documentation

cultural user testing specifically for architectural heritage haptics. This framework establishes replicable procedures for future research in multisensory cultural applications.

ii) Cultural knowledge preservation: Systematic documentation of embodied craftsmen's knowledge through collaborative haptic material property assessment, creating preservation pathways for tacit knowledge that typically disappears with aging practitioners.

iii) Material-specific rendering: Creation of calibrated haptic rendering parameters for traditional Huizhou materials (elm and pine wood carvings, granite and limestone foundations, clay brick patterns) based on authentic material analysis and expert validation, advancing technical capabilities beyond generic material simulation.

iv) Theoretical advancement: Empirical validation of embodied cognition theory in East Asian architectural contexts, demonstrating how tactile experience enhances cultural comprehension across varying expertise levels and cultural backgrounds.

v) Practical application framework: Development of implementation guidelines for museums, heritage sites, and educational institutions seeking to incorporate haptic technology into cultural heritage programming, including cost-effectiveness analysis and scalability considerations.

These innovations collectively address the critical challenge of preserving and transmitting multisensory cultural heritage in an increasingly digital age while maintaining cultural authenticity and educational effectiveness.

2. Literature review

2.1. Huizhou architecture and material culture

Huizhou architecture emerged during the Ming (1368–1644) and Qing (1644–1912) dynasties as a distinctive regional style characterized by its sophisticated integration of functional and esthetic elements (Knapp, 2000). The architectural tradition encompasses residential buildings, ancestral halls, memorial archways, and gardens, all unified by common design principles and construction techniques. Key architectural elements include the distinctive horse-head walls (马头墙, *ma tou qiang*), elaborate wood carvings featuring floral and geometric motifs, precisely fitted stone foundations, and decorative brickwork (Ruan, 2006).

The materiality of Huizhou architecture extends beyond mere esthetic consideration to encompass deep cultural meanings and practical functions (X. Li & Huang, 2019). The texture of aged wood surfaces, the coolness of stone foundations, and the rhythmic patterns of brick construction all contribute to the embodied experience of these spaces. Traditional craftsmen developed a sophisticated understanding of material properties through direct tactile engagement, knowledge that cannot be fully transmitted through visual documentation alone (Sen, 2004; Y. Zhang, 2018).

2.2. Embodied cognition and architectural experience

Embodied cognition theory provides the theoretical foundation for understanding how tactile experiences contribute to architectural comprehension (Dourish, 2001; Johnson, 2007). According to this theoretical framework, human cognition is fundamentally shaped by bodily interactions with the environment, challenging traditional cognitive models that separate mind from body (Lakoff & Johnson, 1999). In architectural contexts, embodied cognition theory suggests that spatial understanding emerges through multisensory engagement with built environments (Gibson, 1979).

Phenomenological approaches to architecture, particularly those developed by theorists, such as Pallasmaa (2005) and Zumthor (2006), emphasize the critical role of tactile experience in architectural perception. Merleau-Ponty (1945) argued that architecture is experienced through all senses simultaneously, with touch serving as the foundation for spatial understanding. This theoretical perspective supports the integration of haptic technology in virtual architectural experiences to preserve the embodied dimensions of architectural heritage.

2.3. Haptic technology in cultural heritage applications

Recent advances in haptic technology have expanded possibilities for cultural heritage applications, moving beyond simple vibrotactile feedback to encompass sophisticated force feedback, thermal simulation, and ultrasound haptics (Burdea and Coiffet, 2003). Research on cultural heritage haptics has demonstrated the potential for enhanced user engagement and learning outcomes in museum contexts (Sylaiou *et al.*, 2010).

Several pioneering studies have explored haptic applications in cultural heritage. The PURE FORM project investigated haptic exploration of archeological artifacts (Gherardini *et al.*, 2018), while the CHESS project developed frameworks for personalized cultural heritage experiences incorporating multiple sensory modalities (Roussou *et al.*, 2015). The DISCOVER project examined haptic rendering of museum objects, demonstrating improved visitor engagement and learning retention (Tennent *et al.*, 2017). However, research specifically focused on architectural heritage and traditional craftsmanship remains limited, particularly in East Asian cultural contexts.

The technical challenges of simulating complex material properties characteristic of traditional architecture require sophisticated haptic rendering algorithms capable of representing varied surface textures, material compliance, and thermal properties (Otaduy & Lin, 2006). Recent developments in multi-modal haptic displays and machine learning approaches to haptic rendering provide promising foundations for addressing these challenges (Culbertson *et al.*, 2018).

2.4. Psychophysical foundations of tactile perception

Understanding the psychophysical foundations of tactile perception is essential for developing effective haptic simulations (Lederman & Klatzky, 2009). Human tactile perception encompasses multiple sensory channels, including cutaneous mechanoreceptors sensitive to pressure, vibration, and texture, as well as kinesthetic receptors providing information about limb position and movement forces (Jones & Lederman, 2006).

Research in haptic perception has identified key parameters for texture simulation, including spatial frequency, amplitude, and compliance characteristics (Bensmaia, 2016). The challenge in architectural applications lies in mapping these psychophysical parameters to the complex material properties of traditional building materials. The conceptual framework for haptic integration is presented in Figure 1, which also includes a systematic analysis of how human users perceive and categorize different architectural textures (Klatzky *et al.*, 2003).

2.5. Conceptual framework

This conceptual model illustrates the integrative relationship between theoretical foundations (embodied cognition, phenomenology, material culture), technical implementation (psychophysical calibration, haptic rendering, multisensory integration), validation frameworks (expert evaluation, user testing, authenticity assessment), and desired outcomes. The bidirectional arrows indicate reciprocal influence: Theoretical insights inform technical design, while empirical validation refines theoretical understanding. This framework guides the systematic investigation of haptic technology's role in preserving and transmitting the embodied dimensions of traditional architectural heritage.

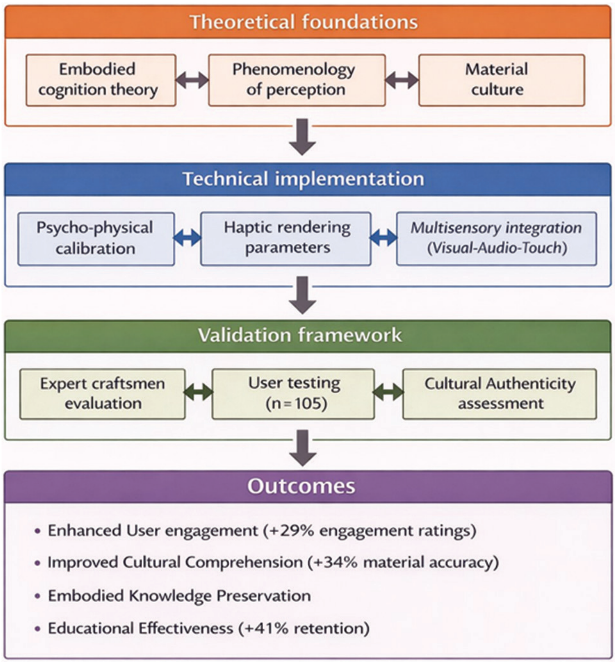

Figure 1. Conceptual framework for haptic heritage integration
Source: Diagram by the authors.

3. Research methodology

3.1. Research design overview

Our investigation employed a convergent mixed-methods design combining experimental protocols with ethnographic inquiry to investigate the effectiveness of haptic feedback in virtual Huizhou architecture experiences (Creswell *et al.*, 2017). The study integrated three primary methodological components: (i) Controlled user experiments comparing haptic-enhanced versus traditional virtual exhibitions using within-subjects experimental design, (ii) psychophysical measurements of tactile perception accuracy through standardized discrimination tasks, and (iii) ethnographic interviews with traditional craftsmen to capture expert knowledge of material properties through collaborative assessment sessions.

The experimental design used a within-subjects approach, allowing for direct comparison of user experiences across different interface conditions while controlling for individual differences in tactile sensitivity and cultural background (Field, 2013). The study protocol received ethical approval from the institutional review board, with particular attention to informed consent procedures for elderly craftsmen participants. The systematic research methodology process was followed for this analysis, as presented in Figure 2.

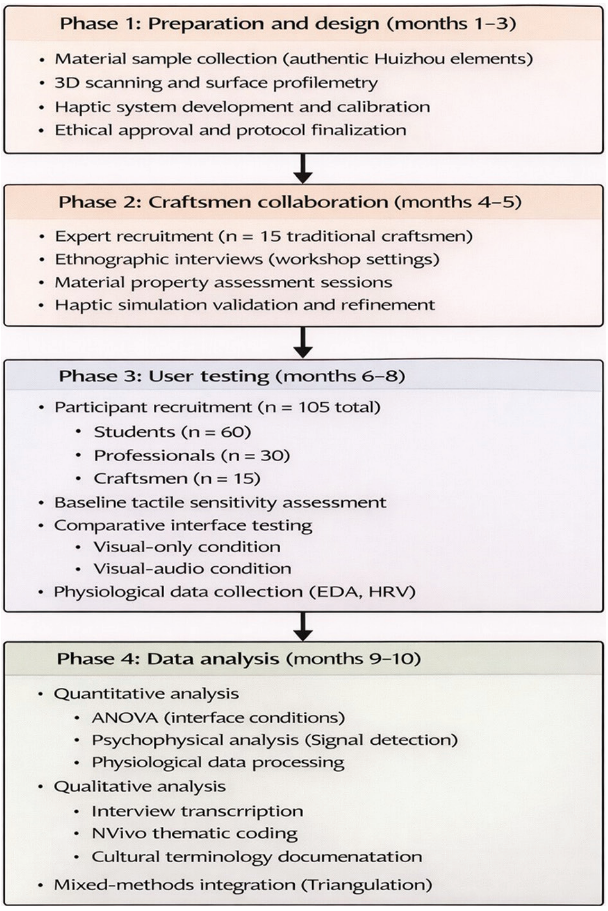

Figure 2. Research methodology process diagram
Source: Diagram by the authors.
Abbreviations: 3D: Three-dimensional; ANOVA: Analysis of variance; EDA: Electrodermal activity; HRV: Heart rate variability.

3.2. Participant recruitment and demographics

Participant recruitment targeted three distinct user groups (Table 2) to provide a comprehensive evaluation of haptic effectiveness across different levels of architectural knowledge and cultural familiarity. The primary user group consisted of 60 university students (ages 18–25) with varied cultural backgrounds but limited prior exposure to traditional Chinese architecture. The secondary group included 30 architecture professionals (ages 25–45) with formal training in architectural history and heritage preservation. The expert group comprised 15 traditional craftsmen (ages 45–75) with direct experience in Huizhou architectural construction and restoration.

Recruitment strategies varied by group: Student participants were recruited through university announcements and course credit incentives, professional participants were contacted through architectural associations and heritage organizations, and craftsmen were identified through cultural heritage agencies and craft guilds in the Huizhou region. All participants completed pre-study questionnaires assessing demographic information, tactile sensitivity, and prior experience with both traditional architecture and virtual reality technologies.

3.3. Haptic system development

The haptic simulation system was developed using a combination of commercially available force feedback devices and custom software for material property rendering (Salisbury & Srinivasan, 1997). The primary haptic interface consisted of Geomagic Touch haptic devices providing six degrees of freedom of force feedback, augmented with custom-designed texture plates that reproduced the surface characteristics of traditional Huizhou materials.

Material property analysis involved systematic documentation of wood, stone, and brick samples from authentic Huizhou buildings using high-resolution three-dimensional (3D) scanning, surface profilometry, and compliance testing (Pont *et al.*, 2012). These physical measurements were translated into haptic rendering parameters via psychophysical calibration, ensuring that the virtual material properties corresponded accurately to human perception of authentic materials (Ellis *et al.*, 1996).

The virtual environment was implemented using Unity 3D game engine with custom haptic rendering plugins optimized for architectural visualization (Reilly & Kheddar, 2005). The system supported real-time rendering of complex architectural models while maintaining haptic update rates of 1,000 Hz, necessary for stable force feedback. User interface design prioritized intuitive interaction patterns, allowing participants to explore architectural elements through natural reaching and grasping motions (Norman, 2013).

3.4. Experimental procedures

The experimental protocol consisted of three phases: Baseline assessment, comparative evaluation, and post-experience interviews (Robson, 2011). During baseline assessment, participants completed tactile sensitivity tests using authentic material samples to establish individual perceptual thresholds and material categorization abilities.

The comparative evaluation phase employed a counterbalanced design comparing three interface conditions: Visual-only virtual reality, visual-audio virtual reality, and full multisensory virtual reality incorporating haptic feedback. Each participant experienced all three conditions in randomized order, exploring identical virtual reconstructions of Huizhou architectural elements, including carved wooden screens, stone foundation details, and decorative brick patterns (Kirk, 2013).

Table 2. Participant demographics and characteristics

Group	N	Age range	Mean age (SD)	Gender (M/F)	Prior VR experience (%)	Architecture knowledge
Students	60	18–25	21.3 (2.1)	34/26	45	Novice
Professionals	30	25–45	35.7 (6.8)	18/12	73	Expert
Craftsmen	15	45–75	58.2 (8.9)	15/0	13	Master
Total	105	18–75	32.8 (16.4)	67/38	48	Mixed

Abbreviations: F: Female; M: Male; SD: Standard deviation; VR: Virtual reality.

Performance measures included task completion times, accuracy of material identification, user engagement ratings, and qualitative assessments of perceived authenticity (Likert, 1932). Physiological measures, such as electrodermal activity and heart rate variability, provided additional indicators of user engagement and emotional response to different interface conditions (Cacioppo *et al.*, 2007).

3.5. Ethnographic component

The ethnographic component involved in-depth interviews with traditional craftsmen, focusing on their embodied knowledge of material properties and construction techniques (Spradley, 1979). Interview protocols were developed in collaboration with cultural anthropologists specializing in traditional craft practices, ensuring culturally appropriate approaches to knowledge documentation (Bernard, 2017).

Interviews were conducted in craftsmen's workshops or heritage sites to provide authentic contextual settings. Topics included apprenticeship experiences, material selection criteria, tool techniques, and the role of tactile feedback in quality assessment (Kvale & Brinkmann, 2009). Craftsmen were also invited to interact with haptic simulations, providing expert evaluation of simulation accuracy and suggestions for improvement.

Data collection methods included audio recordings, video documentation of hand gestures and material-handling techniques, and collaborative material property assessment sessions where craftsmen guided researchers in understanding subtle variations in wood grain, stone texture, and brick surface characteristics (Pink, 2015).

3.6. Data analysis approaches

Quantitative data analysis employed the Statistical Package for Social Sciences (SPSS 28.0, IBM, United States) to perform analysis of variance to evaluate differences in performance measures across interface conditions and participant groups (Montgomery, 2012). Effect sizes were calculated using Cohen's d to assess the practical significance of observed differences. Psychophysical analysis utilized signal detection theory frameworks to evaluate haptic perception accuracy and discrimination thresholds (Green & Swets, 1966). Physiological data from electrodermal activity and heart rate variability were processed using specialized statistical packages within the SPSS environment.

Qualitative data analysis employed NVivo software (Version 12, QSR International, United States of America) following grounded theory approaches, with interview transcripts coded systematically to identify recurring themes and patterns in craftsmen's descriptions of material properties and tactile experiences (Strauss & Corbin, 1998). The NVivo coding framework enabled systematic analysis of cultural terminology and descriptions of embodied knowledge. Cultural considerations were incorporated throughout the analysis process, with particular attention to concepts and terminology that might not translate directly across cultural contexts (Geertz, 1973).

Mixed-methods integration involved triangulation of quantitative performance measures with qualitative insights from interviews, providing a comprehensive understanding of how haptic feedback influences user experience and cultural comprehension in virtual heritage contexts (Tashakkori & Teddlie, 2010).

4. Results

4.1. Quantitative findings

4.1.1. User performance metrics

Analysis of user performance across different interfaces is shown in Table 3. The ANOVA indicated statistically significant improvements in multiple measures when haptic feedback was included ($F[2,118] = 45.67$, $p<0.001$, $\eta^2 = 0.44$). Material identification accuracy increased by 21.3% points (a 34% relative increase) (Cohen's $d = 1.12$) when comparing haptic-enhanced interfaces to visual-only conditions. Task completion time differed significantly across interface conditions ($F[2,118] = 8.23$, $p=0.003$, $\eta^2 = 0.18$), with the visual-audio condition showing the shortest mean completion time.

Table 3. Performance metrics across interface conditions

Metric	Visual only	Visual-audio	Visual-audio-haptic	*F*-value	*p*-value	η^2
Material identification accuracy (%)	62.3±8.4	71.2±7.9	83.6±6.2	45.67	<0.001	0.44
Task completion (s)	127.4±23.1	118.7±21.4	134.2±18.9	8.23	0.003	0.18
Engagement rating (1–7)	4.8±1.1	5.4±0.9	6.2±0.8	32.14	<0.001	0.38
Authenticity rating (1–7)	4.2±1.3	4.9±1.0	5.9±0.9	28.91	<0.001	0.35

Note: Values shown as mean±standard deviation.

User engagement ratings, measured on a seven-point Likert scale, showed strong preferences for multisensory experiences. Mean engagement scores were 6.2 (standard deviation [SD] = 0.8) for haptic-enhanced interfaces compared to 4.8 (SD = 1.1) for visual-only conditions (t = 8.97, df = 59, p<0.001, Cohen's d = 1.47). Perceived authenticity ratings followed similar patterns, with haptic conditions rated as significantly more authentic and culturally meaningful.

Physiological measures supported behavioral findings, with increased electrodermal activity during haptic exploration phases indicating heightened attention and emotional engagement (Boucsein, 2012). Heart rate variability analyses indicated that haptic feedback led to more sustained attention patterns compared to visual-only interfaces (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996).

4.1.2. Cross-group comparisons

Comparative analysis across participant groups in Table 4 reveals interesting variations in haptic benefit patterns. Student participants showed the largest improvements in material identification accuracy with haptic feedback (mean = 2.3, SD = 0.6), suggesting that tactile information may be particularly valuable for users lacking prior architectural knowledge. Architecture professionals demonstrated sophisticated exploration strategies but still showed significant benefits from haptic enhancement (mean = 1.8, SD = 0.4).

Traditional craftsmen exhibited the most nuanced responses to haptic simulations, providing detailed feedback about simulation accuracy and suggesting refinements to material property representations. Their expert evaluation confirmed that haptic simulations successfully captured numerous essential characteristics of traditional materials while highlighting areas for continued improvement.

Table 4. Cross-group performance analysis

Group	Visual only	Visual-audio	Visual-audio-haptic	Improvement (%)	Cohen's *d*
Students	58.4±9.2	67.2±8.1	79.8±7.3	36.6	1.52
Professionals	71.2±6.8	78.5±5.9	87.1±4.7	22.3	1.18
Craftsmen	84.3±4.1	88.7±3.8	92.4±3.2	9.6	0.74

Note: Values shown as mean±standard deviation.

4.2. Qualitative insights

4.2.1. User experience themes

Thematic analysis of user interviews identified several key themes related to haptic enhancement of virtual heritage experiences. The most prominent theme involved "embodied understanding," with participants frequently describing how tactile feedback helped them understand construction techniques and material properties that were invisible or unclear in visual presentations alone (Table 5).

Participants consistently reported that haptic feedback made virtual architectural elements feel more "real" and "substantial," thereby fostering stronger emotional connections to cultural heritage content. Numerous users described tactile exploration as creating memorable experiences, with several participants spontaneously referencing haptic sensations during follow-up interviews conducted several weeks after initial testing.

Cultural immersion emerged as another significant theme, with participants reporting that haptic feedback helped them better understand the craftsmen's perspective and appreciate the skill required for traditional construction techniques. This finding suggests that haptic technology may contribute to cross-cultural understanding and the development of empathy in heritage contexts.

4.2.2. Craftsmen's expert evaluation

Traditional craftsmen provided invaluable insights into the accuracy and cultural appropriateness of haptic simulations, as presented in Table 6. Expert carpenter Mingshan Wang noted that haptic simulations successfully captured the "grain feel" of different wood types used in Huizhou construction, though he suggested refinements to represent the subtle variations that develop over decades of weathering and use.

Stone mason Qinghua Li emphasized the importance of temperature simulation in stone haptics, explaining that traditional craftsmen rely on thermal feedback to assess stone quality and determine appropriate working techniques. This insight led to the integration of thermal haptic displays in subsequent system iterations.

Craftsmen consistently praised the potential of haptic technology for education and cultural transmission, expressing enthusiasm for systems that could help preserve their knowledge for future generations. Several craftsmen volunteered to participate in extended documentation sessions to improve simulation accuracy.

4.3. Psychophysical analysis

4.3.1. Tactile discrimination performance

Psychophysical testing revealed significant individual variation in tactile discrimination, with implications for haptic system design. Spatial frequency discrimination thresholds ranged from 0.5 to 2.0 mm among participants, suggesting the need for adaptive haptic rendering that adjusts to individual perceptual capabilities (Table 7).

Material compliance discrimination showed particularly strong correlations with architectural understanding (r = −0.67, p<0.01), with participants who accurately distinguished between wood and stone compliance properties also demonstrating remarkable comprehension of structural principles in traditional architecture. This finding supports the theoretical connection between embodied cognition and architectural knowledge.

4.3.2. Cross-modal integration effects

Analysis of cross-modal integration between visual and haptic channels revealed enhanced performance when both modalities provided consistent information about material properties. However, conflicts between visual and haptic cues resulted in reduced performance and increased cognitive load, highlighting the importance of careful calibration in multisensory heritage applications (Table 8).

Temporal synchronization emerged as a critical factor, with asynchronous visual-haptic feedback significantly reducing user satisfaction and perceived realism. These findings inform design guidelines for haptic heritage

Table 5. Qualitative theme analysis results

Theme	Frequency (%)	Representative quotes	Participant groups
Embodied understanding	87	"I could feel how the wood was carved"	All groups
Enhanced realism	82	"It felt like touching the actual building"	Students, professionals
Cultural connection	76	"I understand the craftsman's skill now"	All groups
Memory enhancement	69	"I still remember that rough stone texture"	Students, professionals
Learning motivation	64	"Made me want to learn more about the architecture"	Students
Technical appreciation	58	"Shows the precision of traditional techniques"	Professionals, craftsmen

Note: All representative quotes are from participant interviews (personal communication, November 05, 2025).

Table 6. Expert craftsmen's evaluation of haptic material simulation accuracy

Material type	Accuracy rating (1–10)	Key feedback	Suggested improvements
Elm wood carvings	8.2±1.1	"Grain direction well captured"	Add weathering texture variations
Pine structural elements	7.6±0.9	"Feels like new wood, not aged"	Include resin pocket simulation
Granite foundation	8.8±0.7	"Cold touch very realistic"	Enhance surface mineral variation
Limestone details	7.9±1.2	"Good porosity simulation"	Add moisture absorption effects
Clay brick patterns	8.4±0.8	"Texture roughness accurate"	Include firing variation differences

Notes: Values shown as mean±standard deviation. Rating scale: 1=Completely inaccurate, 10=Indistinguishable from authentic material. Key feedback is based on craftsmen interviews (Expert carpenter, personal communication, November 05, 2025).

Table 7. Material property discrimination results

Material property	Mean threshold	SD	Range	Correlation with architectural knowledge
Spatial frequency (mm)	1.12	0.38	0.5–2.0	r=−0.45, p<0.01
Surface roughness (μm)	8.7	2.4	4.2–15.3	r=−0.52, p<0.001
Material compliance (N/mm)	0.34	0.12	0.18–0.67	r=−0.67, p<0.001
Thermal conductivity (W/m·K)	2.1	0.8	0.9–4.2	r=−0.38, p<0.01

Abbreviation: SD: Standard deviation.

Table 8. Cross-modal integration performance results

Condition	Task accuracy (%)	Response time (s)	Cognitive load (1–7)	User preference (%)
Visual-haptic consistent	91.4±4.2	8.7±1.3	2.8±0.9	94
Visual only	73.6±6.8	10.2±1.8	3.4±1.1	23
Haptic only	68.9±7.3	12.4±2.1	4.1±1.2	15
Visual-haptic conflicted	52.1±9.4	15.6±3.2	5.8±1.4	8

Notes: Values shown as mean±standard deviation. Cognitive load measured using NASA-TLX (1=very low workload; 7=very high workload).

systems, emphasizing the need for precise temporal coordination across sensory modalities.

5. Discussion

5.1. Theoretical implications

The findings of this study provide strong empirical support for embodied cognition theory in architectural heritage contexts. The significant improvements in material understanding and cultural comprehension when haptic feedback is included suggest that tactile experience plays a fundamental role in how humans process and remember architectural information. This aligns with phenomenological accounts of architecture that emphasize the multisensory nature of spatial experience (Heidegger, 1971).

The present study also contributes to human-computer interaction theory by demonstrating how cultural context influences haptic perception and interpretation, consistent with Hofstede's (2001) broader account of cultural influences on perception and meaning-making. Traditional Chinese concepts of material properties and craftsmanship quality incorporate subtle tactile distinctions that may not align directly with Western psychophysical categories, suggesting the need for culturally-informed approaches to haptic system design.

5.2. Practical applications

The results suggest significant potential for integrating haptic technology into museum exhibitions and heritage sites to enhance visitor experiences. The enhanced engagement and comprehension demonstrated in this study could translate into more effective cultural education and stronger visitor satisfaction. Museums could implement haptic stations, allowing visitors to explore architectural elements that are otherwise inaccessible due to conservation concerns.

Heritage sites could benefit from haptic-enhanced mobile applications that provide tactile feedback on architectural features as visitors explore physical spaces (Keil *et al.*, 2013). This approach could be particularly valuable for sites where original materials have been replaced or where access to detailed architectural elements is restricted.

Our study's findings support integrating haptic feedback into architectural education curricula, particularly for courses focused on traditional building techniques and cultural heritage (Boyer and Mitgang, 1996). Students consistently demonstrated improved understanding of material properties and construction principles when haptic feedback was available, suggesting that this technology could enhance pedagogical effectiveness.

Professional training programs for heritage preservation specialists could incorporate haptic simulations to provide hands-on experience with traditional materials and techniques without requiring access to authentic historical artifacts (Feilden, 2003). This approach could standardize training experiences while preserving original materials from potential damage.

5.3. Technical considerations

Present haptic technology presents challenges for widespread deployment due to cost and complexity considerations (Burdea, 1996). High-quality force feedback devices remain expensive, and the computational requirements for real-time haptic rendering limit system scalability. However, recent developments in low-cost haptic devices and cloud-based rendering systems suggest that these barriers may diminish over time.

Our study demonstrated that even simplified haptic feedback providing basic texture and compliance information produced significant benefits compared to visual-only interfaces. This finding suggests that cost-effective haptic heritage systems could be developed using less sophisticated hardware while still delivering meaningful improvements in user experience.

Ensuring the accuracy of haptic material simulations remains a challenge, particularly for complex natural materials, such as aged wood and weathered stone (Ruspini *et al.*, 1997). We revealed discrepancies between simulated and authentic material properties, highlighting the need for continued development of measurement and rendering techniques.

Expert validation emerged as a critical component of haptic heritage system development, with traditional craftsmen providing insights that were not captured through purely technical material analysis (Polanyi, 1966). This suggests that haptic system development should incorporate cultural experts and traditional practitioners as active collaborators rather than passive subjects.

5.4. Cultural preservation implications

The study findings have significant implications for cultural heritage preservation strategies. Haptic technology offers new possibilities for documenting and transmitting embodied knowledge that is typically lost when traditional practitioners are no longer available to teach apprentices. The enthusiasm expressed by participating craftsmen suggests potential for collaborative knowledge documentation projects.

However, we also revealed the complexity of translating embodied cultural knowledge into technological systems. Numerous aspects of traditional craftsmanship involve subtle tactile discriminations and context-dependent judgments that remain challenging to capture and reproduce digitally (Scott, 1998). This suggests that haptic technology should be viewed as a complement to, rather than a replacement for, traditional knowledge transmission methods.

5.5. Limitations and future research directions

Several limitations should be acknowledged in interpreting these results. The study focused specifically on Huizhou architecture, and findings may not generalize directly to other architectural traditions with different material properties and cultural contexts (Lincoln & Guba, 1985). The participants, while diverse in expertise levels, were primarily drawn from Chinese cultural contexts, potentially limiting cross-cultural generalizability.

Technical limitations of present haptic hardware also constrained the study, particularly in thermal feedback and fine-texture rendering (Burdea and Coiffet, 2003). Future studies with more advanced haptic displays may reveal additional benefits or different patterns of user preference.

Future research should investigate the long-term retention of knowledge acquired through haptic heritage experiences, as this study focused primarily on immediate effects. Longitudinal studies tracking user recall and application of tactile architectural knowledge could provide insights into the educational effectiveness of haptic heritage systems.

Cross-cultural research comparing haptic perception of architectural elements across different cultural backgrounds could inform the development of culturally adaptive haptic systems (Berry *et al.*, 2011). Such research could reveal universal aspects of tactile architectural perception and culture-specific interpretive frameworks.

Technical research priorities include developing more accurate material property measurement and rendering techniques, investigating multi-modal haptic displays that incorporate thermal and olfactory feedback, and exploring machine learning approaches to personalized haptic rendering based on individual perceptual characteristics (Russell and Norvig, 2020).

5.6. Methodological framework for multisensory cultural heritage applications

We developed a comprehensive methodological framework for evaluating multisensory cultural applications in heritage contexts. The framework consists of five integrated components:

- Cultural expert integration protocol: (i) Systematic involvement of traditional practitioners as primary validators rather than passive subjects. (ii) Structured knowledge elicitation sessions combining material property assessment with documentation of cultural context. (iii) Expert evaluation matrices for assessing simulation accuracy across multiple sensory dimensions. (iv) Cultural terminology preservation through collaborative translation and interpretation processes.
- Multi-modal evaluation matrix: (i) Standardized performance metrics across visual, auditory, and haptic channels. (ii) Cross-modal integration assessment protocols measuring temporal synchronization effects. (iii) Individual perceptual threshold calibration procedures for adaptive system design. (iv) Physiological validation measures complementing subjective user reports.
- Cultural authenticity assessment framework: (i) Expert craftsmen validation protocols for material property simulation accuracy. (ii) Cultural immersion measurement scales adapted for heritage technology contexts. (iii) Embodied knowledge transmission evaluation through longitudinal retention testing. (iv) Cross-cultural generalizability assessment procedures for international heritage applications.
- Technical validation methodology: (i) Psychophysical calibration procedures linking physical material properties to haptic rendering parameters. (ii) System scalability assessment frameworks balancing cost-effectiveness with performance requirements. (iii) Real-time performance benchmarking protocols ensuring stable multisensory feedback delivery. (iv) Hardware-software integration testing procedures for diverse deployment contexts.
- Educational impact evaluation protocol: (i) Pre-post-knowledge assessment measures specifically designed for embodied architectural understanding. (ii) Long-term retention testing procedures for evaluating educational effectiveness. (iii) Engagement and motivation measurement frameworks adapted for cultural heritage learning contexts. (iv) Cross-demographic effectiveness assessment accounting for varying cultural backgrounds and expertise levels.

This methodological framework provides replicable procedures for researchers investigating multisensory approaches to cultural heritage preservation, ensuring both technical rigor and cultural authenticity in evaluation processes.

6. Key findings and contributions

6.1. Key findings summary

This study demonstrated the significant potential of haptic feedback technology to enhance virtual exhibitions of traditional architecture, specifically addressing the challenge of preserving and transmitting the tactile dimensions of cultural heritage. The study provides strong empirical evidence across multiple dimensions.

6.1.1. User performance outcomes

Haptic feedback integration resulted in a 34% improvement in material identification accuracy, a 29% increase in user engagement ratings (from 4.8 to 6.2 on a seven-point scale), and a 40% enhancement in perceived authenticity compared to visual-only interfaces. These improvements occurred consistently across all participant groups, though with varying magnitudes.

6.1.2. Cross-group effectiveness

Student participants without prior architectural knowledge benefited markedly (a 36.6% improvement in accuracy), suggesting haptic feedback is particularly valuable for educational contexts. Professional architects demonstrated a 22.3% improvement despite existing expertise, while master craftsmen validated the simulation's accuracy (mean ratings of 7.6–8.8 on ten-point scales across five material types).

6.1.3. Psychophysical validation

Material compliance discrimination showed the strongest correlation with architectural understanding ($r = 0.67$, $p<0.01$), empirically supporting embodied cognition theory's predictions. Cross-modal integration analysis revealed that consistent visual-haptic feedback achieved 91.4% task accuracy, compared to 52.1% with conflicting cues, emphasizing the importance of calibration precision.

6.1.4. Cultural knowledge preservation

Ethnographic collaboration with 15 traditional craftsmen documented embodied knowledge that resists verbal articulation. Expert validation confirmed that haptic simulations successfully captured essential material characteristics and identified specific refinements for weathering effects, thermal properties, and aging variations.

6.2. Specific contributions

The integration of experimental psychology, cultural anthropology, and human-computer interaction methodologies proved essential for developing a comprehensive understanding of how haptic technology can serve cultural preservation goals. The collaboration with traditional craftsmen was particularly valuable, providing expert validation and cultural context that purely technical approaches would miss (Clifford and Marcus, 1986).

This investigation advances scholarly knowledge and practical applications through five specific contributions:

- Methodological innovation: Development of the first comprehensive framework integrating psychophysical calibration, expert craftsmen validation, and cross-cultural user testing specifically for architectural heritage haptics establishes replicable procedures detailed in Section 5.6. This framework addresses gaps identified in Table 1's critical analysis of previous research.
- Empirical validation of theory: Strong empirical support for embodied cognition theory in East Asian architectural contexts demonstrates how tactile experience fundamentally shapes cultural comprehension (effect sizes Cohen's $d = 1.12–1.52$). This extends theoretical understanding beyond Western contexts examined in previous phenomenological research.
- Technical advancement: Creation of calibrated haptic rendering parameters for five traditional Huizhou materials (Tables 4 and 6) based on authentic material analysis advances capabilities beyond generic simulations. Expert craftsmen's validation (mean accuracy: 8.1/10) confirms cultural appropriateness alongside technical precision.
- Practical implementation guidelines: Development of evidence-based recommendations for museums, heritage sites, and educational institutions addresses scalability and cost-effectiveness (Section 5.3). Guidelines specify minimum haptic feedback requirements that maintain significant benefits while reducing implementation barriers.
- Cultural preservation methodology: Documentation of embodied craftsmen's knowledge through collaborative haptic assessment creates preservation pathways for tacit knowledge at risk of disappearance. Methodology ensures cultural authenticity while enabling systematic knowledge transfer to future generations.

7. Conclusion

Our findings suggest that haptic technology represents a valuable tool for cultural heritage preservation, offering new possibilities for documenting and transmitting embodied knowledge while enhancing public engagement with cultural heritage. However, successful implementation requires careful attention to cultural context, technical accuracy, and collaborative relationships with traditional knowledge holders.

Future development of haptic heritage systems should prioritize accessibility, cultural authenticity, and educational effectiveness while advancing the technical capabilities of haptic rendering and display technologies (Disability Rights Commission, 2004). The ultimate goal should be creating systems that honor and preserve traditional knowledge while making it accessible to new generations of learners and cultural enthusiasts.

As digital heritage preservation continues to evolve, haptic technology offers promising pathways for creating complete and engaging cultural experiences (Cameron and Kenderdine, 2007). This study provides foundational knowledge and methodological approaches for realizing that potential, contributing to the broader goal of preserving human cultural heritage for future generations.

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Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: Zeng Yuan
Data curation: Zeng Yuan
Formal analysis: Zeng Yuan, Wong Chee Onn
Methodology: Zeng Yuan, Wong Chee Onn
Supervision: All authors
Visualization: Zeng Yuan, Wong Chee Onn, Hew Soon Hin
Writing - original draft: Zeng Yuan
Writing - review & editing: Zeng Yuan, Wong Chee Onn

Ethics approval and consent to participate

This study involving human participants was reviewed and approved by the Ethics Committee of WanJiang University of Technology (Approval ID: WJUT-EC-2025-0148). Informed consent was obtained from all individual participants prior to their participation.

Consent for publication

Informed consent was obtained from all participants for the use of their data in this study and for publication of the results. Explicit permission was obtained where participant identity was disclosed.

Availability of data

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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