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Article

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ABSTRACT

To address the limitations of current digital cultural tourism, which is predominantly centered on auditory and visual stimuli and often lacks deep, embodied engagement, this paper presents the design and evaluation of an immersive cultural tourism solution for the Silk Road. The core of the system is a smart textile wearable, the "Silk Road Traveler's Robe" (SRTR), which integrates a flexible haptic feedback array, a temperature module, and dynamic lighting units. This robe communicates in real-time with an augmented reality (AR) application via Bluetooth Low Energy (BLE). The AR application digitally reconstructs significant Silk Road cultural scenes, such as the Dunhuang Grottoes and Kuqa music and dance. By mapping virtual events to the wearable device's physical feedback, the system facilitates a multi-sensory, immersive cultural exploration. A comparative study involving 30 participants was designed to assess the system's effectiveness. The results showed that the experimental group using the SRTR system exhibited significantly higher levels of immersion, presence, and cognitive efficiency regarding cultural information ($p < 0.01$) compared to the control group, which used a traditional AR-only experience. This study validates that integrating smart textile wearables enhances the authenticity and emotional connection of cultural experiences, presenting a novel technological approach for the digital cultural tourism industry.

KEYWORDS

smart textiles, wearable devices, immersive experience, cultural tourism, human-computer interaction

INTRODUCTION

The Silk Road is one of the most significant cultural routes in human history. It was not only the main artery for commercial exchange between East and West in ancient times but also a vital channel for the exchange and mutual learning between civilizations. Protecting, preserving, and revitalizing the cultural heritage of the Silk Road is a critical contemporary task. With the rapid development of digital technology, particularly virtual

reality (VR) and augmented reality (AR), digital cultural tourism has emerged. This technology has transcended the temporal and spatial limitations of cultural heritage, providing the public with unprecedented opportunities to experience and learn about history and culture [1].

However, the current mainstream digital cultural tourism model has a significant limitation: a primary focus on audiovisual information, often neglecting other sensory modalities. This neglect can weaken the users' sense of presence, creating a "gap" between the virtual environment and the user and hindering the formation of deep emotional resonance and embodied cognition [2]. Users often feel like bystanders rather than active participants, which greatly reduces the authenticity and impact of the cultural experience. How to move beyond the bottleneck of unimodal sensory engagement and build a multi-channel, highly immersive cultural experience has become a key challenge that the digital cultural tourism field urgently needs to address.

Smart textiles, as an emerging technology that seamlessly integrates electronic components, sensors, and actuators with traditional textiles, offer unique possibilities for addressing these issues [3]. They not only possess the comfort and portability of traditional clothing but can also serve as a physical medium for human interaction with the digital world, transmitting rich tactile, thermal, and other sensory information directly to the skin—the body's largest sensory organ [4].

Based on this, this study explores a novel approach: utilizing smart textile wearables to create an immersive experience where users can "feel" the virtual world. This would allow users exploring a digital Silk Road to not only see and hear but also "touch" the texture of silk, "feel" the temperature variations of the desert, and "experience" the micro-environment of the grottoes.

This paper describes the design, implementation, and evaluation of an immersive cultural tourism experience system for the Silk Road based on a smart textile wearable device. To achieve this, we undertook several key research activities: (1) We designed and developed a prototype smart textile wearable, the "Silk Road Traveler's Robe" (SRTR), which integrates multiple physical feedback modules. (2) We developed a compatible immersive AR application featuring Silk Road cultural themes. (3) We constructed a mapping model and system architecture to translate virtual events into physical feedback. (4) We conducted user experiments to quantitatively and qualitatively evaluate the solution's effectiveness across multiple dimensions, including immersion, presence, and cultural cognition efficiency.

The novelty of this research lies in its systematic application of smart textile technology to construct an immersive experience for the grand cultural theme of the Silk Road. Through the deep integration of

technology and humanities, it aims to move beyond the existing boundaries of digital cultural tourism, providing an effective theoretical framework and practical example for the digital activation and dissemination of cultural heritage.

RELATED WORK

Smart Textiles and Wearable Technology

Smart textiles and wearable technology have become prominent research areas in the field of human-computer interaction in recent years. Early explorations in this field primarily focused on physiological signal monitoring [5]. As technology has advanced, the research focus has gradually shifted toward active interaction and sensory feedback. For example, Google's Project Jacquard embedded conductive yarns into fabric to enable touch and gesture recognition on clothing surfaces [6].

In terms of sensory feedback, haptic feedback has been a central research focus. Researchers have utilized miniature vibration motors, pneumatic actuators, and shape memory alloys to achieve point, linear, and surface-based tactile cues on clothing for navigation, notification, or emotional expression [7]. Additionally, thermal feedback technology has also advanced. By using Peltier effect modules, wearable devices can rapidly generate localized cooling or heating sensations on the skin, greatly enriching the dimensions of interaction [8,9]. However, existing research has mostly focused on general interaction tasks and has not fully integrated these technologies into specific, complex cultural experience scenarios.

Immersive Technologies in Cultural Heritage

In the field of cultural heritage protection and exhibition, VR/AR technology has been widely applied. From the "Digital Palace Museum" project to the VR experiences at the Louvre, these initiatives have successfully brought static cultural artifacts to life [10]. AR technology, particularly mobile AR and AR glasses, has demonstrated great potential in museum tours and site reconstructions due to its ability to superimpose virtual information onto the real environment [11,12]. Although visual effects are becoming increasingly realistic, these applications typically lack physical world interaction and congruent sensory feedback.

Recognizing this limitation, scholars have begun to explore multi-sensory experiences. Some studies have attempted to introduce devices such as fans, odor dispensers, and vibrating floors in specific spaces (e.g., CAVE systems) to enhance immersion [13]. However, these solutions are usually equipment-heavy and costly,

and they restrict users to fixed locations, making personalized and mobile experiences impossible. A current research challenge is how to deliver multi-sensory feedback to users in a lightweight, natural, and personalized manner.

Digital Presentation of Silk Road Culture

The digitization of Silk Road cultural heritage has yielded remarkable results, with the "Digital Dunhuang" project being the most notable example. Through high-precision data collection and 3D modeling, this project has enabled the permanent digital preservation and online sharing of the Dunhuang grottoes [14]. In addition, many research institutions and teams have developed virtual museums, documentaries, and educational games related to the Silk Road [15,16]. These projects have greatly promoted the popularization of Silk Road culture.

However, current digital presentation methods still primarily focus on "displaying," rendering the user experience relatively passive. Viewers can observe exquisite murals and access detailed explanations, but it is difficult for them to personally connect with or develop an embodied understanding of the historical context and the emotions of the people of that time. For instance, through visual observation alone, one cannot feel the chill of the cave or appreciate the hardships of ancient artists painting by candlelight, nor can one sense the harsh natural environment faced by caravans crossing the desert. This "shallow" experience limits the depth and breadth of cultural dissemination.

Summary of Research Gaps

In summary, the current research presents the following gaps:

Technological Integration Gap: There is a lack of research on the systematic integration and application of smart textile sensory feedback technology within complex cultural tourism scenarios.

Sensory Palette Limitation: The current paradigm of digital cultural tourism is constrained by a narrow sensory palette, primarily engaging sight and sound, which often fails to foster a profound sense of presence or emotional connection.

Content Design Gap: The digital content for the Silk Road focuses more on information presentation and lacks an experience design centered on "personal involvement" that can engage users' multiple senses.

This research addresses these gaps. By using a smart textile wearable device as a bridge, it connects virtual Silk Road cultural content with the user's physical perception, aiming to create an unprecedentedly deep and immersive cultural tourism experience.

SYSTEM DESIGN AND METHODOLOGY

This system consists of three core components: a smart textile wearable device (the SRTR), a mobile AR terminal (smartphone or AR glasses), and a cloud server (optional). Its overall architecture is shown in Figure 1.

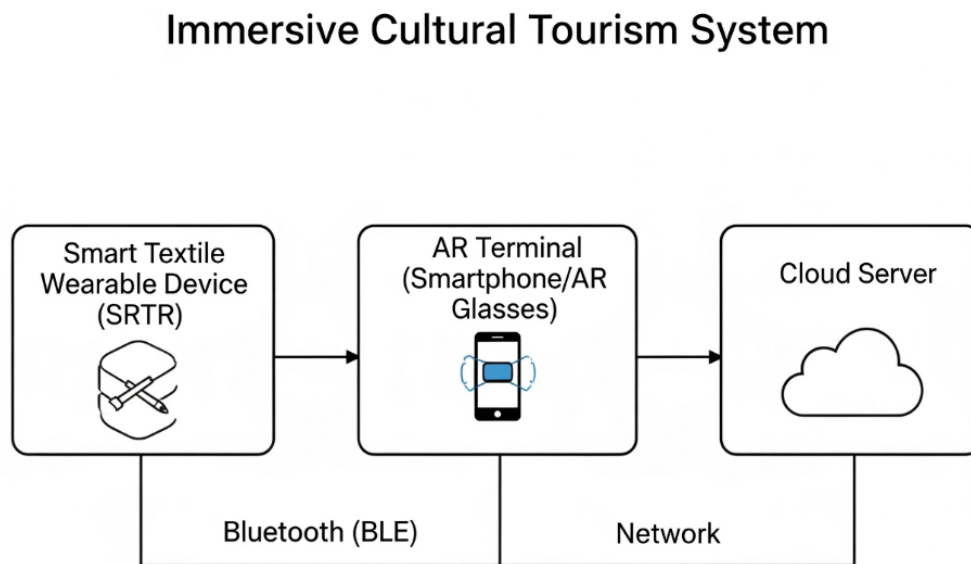


Figure 1. Cloud Server (for scalability & multi-user features)

The workflow is as follows:

- ① The user dons the SRTR and launches the "Silk Road Adventure" application on the mobile AR terminal.
- ② The AR application uses the device's camera to recognize the real environment or uses GPS positioning to overlay 3D digital scenes of Silk Road culture onto the user's view.
- ③ The user's position and orientation are tracked in real-time by the AR terminal's Simultaneous Localization and Mapping (SLAM) or Visual-Inertial Odometry (VIO) system, which fuses data from the camera and IMU.

This provides robust six-degrees-of-freedom (6-DOF) tracking, enabling the user to physically walk around and navigate the superimposed virtual scenes.

- ④ When a user interacts with a specific object (e.g., a piece of silk, a mural) or enters a specific environment (e.g., a desert, a cave) in the virtual world, the AR application triggers a "sensory event".
- ⑤ This event is encoded into instructions and sent to the Central Control Unit (CCU) of the SRTR via the BLE protocol.
- ⑥ The CCU parses the instructions to precisely control the corresponding actuator modules (e.g., the haptic array, temperature unit), thereby generating physical feedback.
- ⑦ The user's body receives this feedback, forming a multi-sensory loop that significantly enhances the sense of immersion and realism.

Clarification on the Role of the "Optional" Cloud Server

The "optional" nature of the cloud server in our system architecture (Figure 1) reflects two distinct operational modes: a standalone mode for the current experimental prototype and a cloud-connected mode envisioned for a full-scale public deployment.

Standalone Mode (for Experimental Prototype)

For the controlled experiment described in this paper, the system operated in a standalone mode. All necessary 3D assets, cultural information, and logic for the three specific scenes (Dunhuang, Kuqa, and Loulan) were pre-packaged within the AR application. This approach ensures experimental consistency and eliminates potential confounding variables from network latency, making the cloud server unnecessary for this validation study.

Cloud-Connected Mode (for Full-Scale Deployment)

For a scalable and dynamic public-facing application, the cloud server becomes an essential component. Its primary roles would include:

Content Delivery Network (CDN)

Hosting and streaming a vast repository of high-fidelity 3D models and multimedia content for numerous cultural sites along the Silk Road. This reduces the initial application size and allows for dynamic content updates.

Multi-User Experience Management

As envisioned for future work, the server would manage user synchronization, interaction states, and communication for collaborative virtual tourism experiences.

Data Management and Personalization

The server would handle user data (with appropriate privacy safeguards) and analytics, enabling personalized feedback models and content recommendations to enhance engagement.

This dual-mode architecture allows for rigorous local prototyping while providing a clear path for future scalability and enriched functionality.

Hardware Design of the Smart Textile Wearable Device (SRTR)

The SRTR is the core of this system, and its design was guided by the key considerations of comfort, integration, and functionality. While creating a functional prototype was the primary goal, efforts were made to enhance wearability, such as using a flexible PCB for the haptic array and selecting a thin, lightweight battery. The exterior design is inspired by the round-collared robes of the Han and Tang dynasties to align with the cultural background of the Silk Road. Its hardware structure is shown in Figure 2.

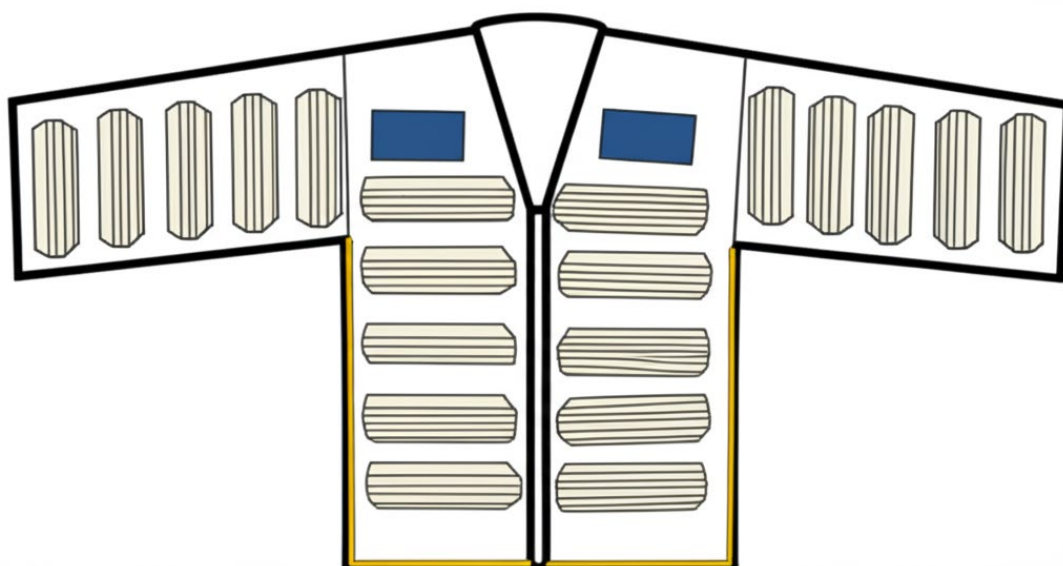


Figure 2. SRTR Hardware Structure and Module Distribution Diagram. Blue part: Micro-environment Simulation Module. Yellow part: Dynamic Lighting Unit

In this diagram, the beige rectangular areas on the torso and sleeves represent the flexible haptic array, the blue squares on the chest represent the temperature feedback module, and the yellow line at the hem represents the dynamic lighting unit. The main hardware modules include:

① **Central Control Unit (CCU):** Utilizes a low-power, high-performance ESP32 microcontroller. It integrates Wi-Fi and BLE 5.0 capabilities and is responsible for receiving instructions from the AR terminal and controlling all actuators.

② **Flexible Haptic Array:** Composed of 24 miniature linear resonant actuators (LRAs), which are encapsulated on a flexible printed circuit board (PCB) and sewn into the inner lining of the garment. These LRAs can operate independently or cooperatively. By precisely controlling their vibration frequency and amplitude, they can simulate various haptic effects, such as the subtle sensation of silk brushing against the skin, the gritty feeling of blowing sand, and the resonance of musical instruments.

③ **Micro-environment Simulation Module:**

Temperature feedback: Four semiconductor cooling/heating chips (TECs) based on the Peltier effect are integrated on the chest. By precisely controlling the current's direction and magnitude with a PWM signal, a relative temperature difference of about 5 °C-10 °C can be achieved within a short time, which is used to simulate the "coolness" of entering a cave or the "heat" of a desert scene. To ensure user safety and comfort, we designed multiple safety mechanisms. The firmware incorporates an absolute temperature safety threshold, limiting skin contact temperature to a safe range (e.g., 15°C to 40°C) to prevent overheating or overcooling. The system also sets a maximum duration for single temperature feedback and includes fail-safe logic. If the sensor detects an abnormal reading, it automatically cuts off module power. At the hardware level, we equipped each TEC module with an independent high-precision thermistor placed near the skin for real-time monitoring and closed-loop feedback control. The circuit design also includes an overcurrent protection mechanism to prevent power overload. These collaborative software and hardware measures ensure user safety during the experience.

Humidity feedback (conceptual design): While not integrated into the current prototype for design simplicity, this is proposed for future work. A micro ultrasonic atomizer could release a small amount of water mist at specific locations to simulate the humid air in a cave.

④ **Dynamic Lighting Unit:** Utilizes programmable, flexible WS2812B RGB LED strips sewn into the hem of the garment. They can change color and brightness according to the virtual scene's atmosphere (e.g.,

candlelight in a cave, brilliant colors of a celebration) to provide ambient visual cues that enhance the environmental atmosphere.

⑤ **Power Management Module:** The system is powered by a thin, lightweight 5000mAh polymer lithium battery. Based on the battery's capacity and the theoretical power consumption of its components, the system is estimated to operate for 1-3 hours under typical use with an optimized power management circuit.

Immersive AR Application and Interaction Design

The AR application was developed using the Unity engine and the AR Foundation framework, ensuring compatibility with mainstream iOS and Android devices. For the content design, we selected three representative cultural nodes along the Silk Road for digital reconstruction:

Scene 1: Dunhuang - The Buddhist Manuscript Repository: Users can "enter" a 1:1 scale reconstruction of the Buddhist Manuscript Repository and "pick up" virtual scrolls using AR. As their hands approach the scrolls, the haptic array on the inner arm of the SRTR generates fine vibrations, simulating the texture of ancient paper. Simultaneously, the temperature module on the chest produces a slightly cool sensation, simulating the cave's constant temperature environment.

Scene 2: Kuqa - Dance Fantasy: The user is immersed in a grand Kuqa dance performance. As virtual instruments (such as the pipa and jiegu drum) are played, the haptic array on the back of the SRTR generates synchronized rhythmic vibrations corresponding to the music's rhythm and intensity, allowing the user to "feel" the sound waves. The lighting units on the robe also flash in time with the music.

Scene 3: Loulan - Desert Journey: Users experience a journey through the desert. The AR view shows a scene of swirling sand. The SRTR generates continuous, random granular haptic feedback to simulate sand blowing against the body. The temperature module produces a sensation of warmth. When the user "drinks" from a virtual water source, the temperature module briefly switches to a cool sensation, providing a strong sensory contrast.

We established a "Virtual Event-Sensory Feedback" (V-S) mapping table and implemented it via scripts in Unity. For example, a "touching silk" event would trigger an instruction packet containing a specific LRA address, a 200Hz vibration frequency, an 80% amplitude, and a 1.5-second duration, which would be sent to the SRTR.

Sensory Feedback Calibration and Parameter Determination

To ensure the sensory feedback was meaningful and perceptually grounded, the parameters in the V-S Mapping Table were determined through a systematic, iterative calibration process conducted prior to the formal experiment, rather than being chosen arbitrarily. This process included the following steps:

Initial Design & Prototyping: We began by creating a library of distinct sensory effects based on haptic design principles. For example, to simulate the "delicacy of silk," we hypothesized that a high-frequency, low-to-medium amplitude continuous vibration would be most effective. Conversely, for the "grittiness of wind and sand," we prototyped a series of random, sharp, short-duration pulses across multiple actuators.

Iterative User-Centered Refinement: We conducted several informal testing sessions with a small group of 5 users (who did not participate in the final experiment). In these sessions, users experienced a specific virtual event (e.g., touching a virtual silk scroll) paired with a corresponding sensory effect. They were then asked to describe the sensation and rate its appropriateness and realism on a 1-5 scale.

Parameter Tuning and Finalization: Based on this qualitative feedback, we iteratively tuned the parameters. For instance, the initial "silk" vibration was perceived as "too much like a phone buzzing". We then experimented by lowering the amplitude and increasing the frequency until users began to describe the feedback as "smoother," "finer," and more "texture-like". The final parameters (e.g., 200Hz frequency, 80% amplitude for "touching silk") were selected once a clear consensus emerged from the test group that the feedback was evocative and clearly distinguishable from other effects.

This calibrated set of parameters was then implemented in the V-S Mapping Table for use in the main comparative experiment. While not a formal pilot study, this user-centered calibration was a crucial methodological step to ensure the sensory feedback was meaningful and perceptually grounded before the formal evaluation.

Digital Reconstruction and Content Authenticity

To ensure content quality and historical authenticity, we followed a structured digital reconstruction process for the AR environments.

Data Sources and Historical Research: Our digital models were based on established academic research and publicly available digital archives, most notably the high-resolution photographs and 3D scan data from the "Digital Dunhuang" project. For artifacts like Kuqa musical instruments and Han and Tang dynasty clothing styles, we consulted historical texts, archaeological reports, and museum collections to guide our designs.

3D Modeling and Texturing: The 3D models were created using industry-standard software (e.g., Blender, ZBrush). Our goal was to achieve a balance between historical accuracy and performance on mobile AR devices. For key architectural elements and artifacts, such as the virtual scrolls, we aimed for high fidelity in shape and proportion. Textures were developed from photographic references of real-world counterparts to simulate authentic materials like aged paper, stone, and textiles.

Integration and Interaction: The created assets were imported into the Unity engine. Interactive objects, such as the virtual scrolls and instruments, were programmed with specific interaction scripts. For instance, the scrolls were given colliders and programmed to trigger haptic events upon an AR "touch," while the instruments were linked to the audio engine and the SRTR's haptic system to synchronize with the music. While not a one-to-one scholarly reconstruction, this methodology ensured that the AR experience was grounded in historical context and provided a high degree of visual and interactive authenticity.

Experimental Design

To quantitatively evaluate the effectiveness of this system, we designed a between-subjects experiment.

Participants: 30 university students (16 male, 14 female; M_age = 22.4 years, SD = 2.1) were recruited and randomly assigned to one of two groups. Each participant was assigned a number upon arrival, and a computer-based random number generator was used to place them in either the Experimental Group (N=15) or the Control Group (N=15).

Experimental Procedure: All participants first completed an information questionnaire designed to gather basic demographic data (age, gender, academic major) and to assess their prior experience with AR and VR, ensuring no significant pre-existing differences in technological familiarity between the groups. Subsequently, participants in each group experienced the three AR scenarios, with each scenario lasting approximately 5 minutes. To control for potential order effects, the presentation sequence of the three scenarios was randomized for each participant. After the experience, participants immediately completed a series of evaluation questionnaires.

Measurement Tools:

Immersion Scale: The Immersion Experience Questionnaire (IEQ) developed by Jennett et al. [17] was used to assess user engagement and the sense of reality during the experience. The scale's Cronbach's α was 0.76.

Presence Questionnaire: The Presence Questionnaire (PQ) by Witmer and Singer [18] was adopted to measure the users' subjective perception of "being present". The scale's Cronbach's α was 0.84.

Cultural Information Cognitive Efficiency Test: After the experience, participants completed a 10-item multiple-choice test covering cultural knowledge points from the scenarios. This was used to measure the effectiveness of different experience modes in knowledge transmission and memory.

Semi-structured Interviews: After the experiment, a brief interview was conducted with each participant to collect qualitative data, such as their subjective evaluations and suggestions for improvement.

Data Analysis: SPSS 26.0 was used for data analysis. An independent samples t-test was used to compare scores on the IEQ and PQ, while a chi-square test (χ^2) was conducted to compare the accuracy rates on the knowledge test, with the significance level set at $\alpha = 0.05$. Thematic analysis was performed on the interview data using NVivo 12. The analysis followed a systematic process: two researchers independently coded a subset of the data (approx. 20%) using open coding. Inter-coder reliability was high (Cohen's Kappa = 0.82). After discussing and finalizing a codebook, one researcher coded the remaining transcripts. The research team then collaboratively reviewed the codes to categorize them into overarching themes.

RESULTS AND ANALYSIS

Statistical Analysis of Questionnaire Data

As shown in Table 1, the scores of the experimental group on all three core measures were significantly higher than those of the control group.

Table 1. The analysis results of the scores of each scale for the two groups of subjects

Measurement dimension	Group	N	Mean	SD	t value	P value
IEQ	Experimental group	15	4.62	0.51	4.92	< 0.001
	Control group	15	3.58	0.64		
PQ	Experimental group	15	4.75	0.48	5.20	< 0.001
	Control group	15	3.61	0.70		

The average IEQ score of the experimental group was 4.62, significantly higher than the control group's score of (3.58) ($t(28) = 4.92, p < 0.001$). This indicates that the introduction of multi-sensory feedback greatly enhanced users' immersion and sense of reality.

The average PQ score of the experimental group was 4.75, significantly higher than that of the control group (3.61; $t(28) = 5.20, p < 0.001$). This confirmed that the physical feedback provided by the SRTR effectively counteracted the "sense of isolation" and enabled users to feel truly "present" in the virtual Silk Road scenarios.

The experimental group's average correct rate on the knowledge test was 88.67%, significantly higher than the control group's rate of 72.00% ($\chi^2(1, N = 30) = 13.19, p < 0.01$). This result is particularly noteworthy, as it suggests that the enhanced immersive experience not only improves entertainment value but also promotes the absorption and retention of cultural knowledge.

Qualitative Interview Analysis

Through transcription and thematic analysis of the interview recordings, we identified the following core themes:

Enhanced Realism and Authenticity: Participants in the experimental group frequently reported that physical feedback was key to enhancing their sense of reality. One participant noted, "When I saw the desert in AR and felt a warm breeze on my neck, for a moment I believed I wasn't in the lab. The feeling was amazing". Another said after experiencing the virtual scroll, "The subtle vibrations made the virtual scroll feel like it had 'weight' and 'texture,' rather than just being a floating model in the air".

Emotion Amplifier: The feedback from the SRTR was regarded as an emotional catalyst. A participant described their experience during the Kuqa dance: "It wasn't just hearing the music; my whole back resonated with the drumbeats. The sense of shock and joy was something you couldn't get from just listening". This indicates that embodied experiences can more effectively evoke users' emotional resonance.

Attentional Guidance: The haptic and thermal feedback played a role in guiding user attention. For instance, when a virtual object was interactive, a slight tactile cue would cause users to subconsciously focus on and explore it, a method they found more natural and intuitive than on-screen UI prompts.

Suggestions for Improvement: Participants also provided valuable suggestions. Key suggestions included: (1) a desire for more delicate and diverse haptic feedback; (2) the need for improved battery life; and (3) a request for more personalized clothing styles and sizes.

Based on the quantitative and qualitative results, the proposed immersive experience solution based on a smart textile wearable device demonstrates significant advantages in enhancing user immersion, presence, and cultural learning outcomes.

DISCUSSION

The results of this study demonstrate that integrating physical sensory channels, such as touch and temperature, into digital cultural tourism via smart textile wearables is an effective method for enhancing immersion. This aligns with Embodied Cognition Theory, which posits that cognitive processes are not confined to the brain but are deeply rooted in the body's interaction with the physical world [2]. When a user's body can "feel" the virtual world, their cognitive system is more likely to accept the "authenticity" of that environment, thereby generating a deeper sense of presence.

The significant improvement in cultural information cognitive efficiency is an especially encouraging finding. This may be attributable to Multichannel Learning Theory, which suggests that presenting information through multiple sensory channels can reduce the cognitive load on any single channel and leverage the complementary nature of different channels to enhance memory encoding [19]. In this study, visual information (murals), auditory information (explanations), tactile information (coolness of grottoes, texture of paper), and kinesthetic information (body movement) are interrelated, forming a rich, contextual learning environment that facilitates the internalization of knowledge. This opens new avenues for "edutainment" in cultural dissemination.

The system proposed in this research has broad potential applications. It can enhance existing museum exhibitions; visitors wearing the SRTR could experience the stories behind cultural relics while viewing the real artifacts. It enables vivid reproductions of historical scenes at heritage sites without altering the physical location. Visitors could freely walk through a vast site and experience the atmosphere of millennia ago. For students of history, archaeology, and art, it provides an interactive and immersive platform that transforms passive learning into active exploration. In terms of cultural and creative products, the SRTR and its associated experiences could be developed into a new type of high-tech cultural product, creating new opportunities for the tourism and cultural industries.

Future research could include developing denser, higher-fidelity flexible haptic displays; integrating other sensory feedback modules, such as smell and wind; and using machine learning algorithms to create personalized user feedback models. The experience content could be expanded from the Silk Road to other cultural themes, such as ancient Egyptian or Mayan civilizations, to build a global repository of immersive digital cultural heritage. Future work will also focus on developing a system for simultaneous multi-user online operation. This would require robust implementation of the cloud server component to manage real-

time synchronization, interaction states, and communication data, allowing users to see and interact with each other in shared virtual cultural scenarios and enhancing the social dimension of the experience.

While the results are promising, this study has several limitations that provide a clear roadmap for future work. First, the generalizability of our findings is limited by the study's scope. The experiment was conducted with a limited sample of 30 university students in a controlled laboratory setting. This demographic may be more technologically adept than the general tourist population. Future work should validate the system's effectiveness with a larger, more diverse demographic—including different age groups and levels of technological literacy—in real-world settings like museums or heritage sites.

Second, the prototype itself has limitations that were outside the scope of this initial evaluation. A formal ergonomics and wearability study was not conducted. The claim of over three hours of battery life is a theoretical estimate based on component specifications; rigorous empirical testing under defined use conditions has not yet been performed. While comfort was a design principle, factors like perceived weight, thermal dissipation, and material feel during prolonged use were not systematically assessed. A rigorous ergonomics evaluation is a critical next step. Furthermore, to achieve more holistic immersion, the sensory palette must be expanded. The current system notably lacks an olfactory (smell) feedback channel, the integration of which remains a significant challenge for future iterations. Addressing these limitations will be pivotal in evolving the SRTR from a promising prototype into a robust system for cultural heritage.

Third, the measurement of cultural cognitive efficiency relied on a 10-item multiple-choice test. This instrument primarily assesses factual recall and may not fully capture the complex construct of cognitive efficiency. Moreover, the high average score in the experimental group (88.67%) suggests a potential ceiling effect, where the test may have been too easy to distinguish among high-performing participants, possibly underestimating the true learning benefit of the immersive system. Future research should employ more sophisticated assessments, such as open-ended questions, problem-solving tasks, or delayed-recall tests, for a more comprehensive evaluation of learning outcomes.

Finally, regarding the qualitative analysis, while inter-coder reliability was established on a subset of the data to create a consistent codebook, the majority of the transcripts were coded by a single researcher. This introduces the potential for subjective interpretation or researcher bias in the analysis of the remaining data. Consequently, the qualitative findings should be interpreted as exploratory insights that illustrate the user experience, rather than as fully objective, generalizable facts.

CONCLUSIONS

This paper addresses the prevalent challenge in digital cultural tourism, where an over-reliance on unimodal (primarily audiovisual) experiences often leads to shallow, disembodied user engagement. It describes the innovative design and implementation of an immersive cultural tourism experience system for the Silk Road based on a smart textile wearable device. By designing the core hardware "Silk Road Traveler's Robe" (SRTR) and developing corresponding AR content, this research successfully integrates vision, hearing, touch, and temperature, constructing a physical feedback loop for a highly immersive experience.

The results of the user experiments clearly demonstrate that this system offers significant advantages over the traditional AR mode in enhancing user immersion, presence, and the efficiency of cultural knowledge acquisition. This study not only provides a specific, feasible technical solution for existing problems in digital cultural tourism but, more importantly, it explores and validates a new paradigm that merges cutting-edge technology with profound humanistic content. This indicates that future cultural tourism will be less about passive "watching" and more about active, multi-sensory, and embodied "experiencing". With the continued maturation of smart materials and human-computer interaction technologies, we have reason to believe that this deeply immersive cultural experience model will play an increasingly important role in the protection, preservation, and innovative development of cultural heritage.

Availability of Data and Materials

The datasets used and/or analysed during the current study were available from the corresponding author on reasonable request.

Author Contributions

Jianqiang Wang and Jingjing Guo designed the study; all authors conducted the study; Jingjing Guo and Jianqiang Wang collected and analyzed the data. Jingjing Guo and Jianqiang Wang participated in drafting the manuscript, and all authors contributed to critical revision of the manuscript for important intellectual content. All authors gave final approval of the version to be published. All authors participated fully in the work, took public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or completeness of any part of the work were appropriately investigated and resolved.

Ethics Approval and Consent to Participate

This survey was conducted in compliance with [Ethics Committee of Henan Economy and Trade Vocational College]. Participants were informed of the study's purpose and data usage prior to participation, and responses were collected anonymously. No personally identifiable information was stored.

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Conflict of Interest

The authors declare no conflict of interest.

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