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Digital Communication of Cultural Heritage as the Medium for Fluoride Cognition: Intangible Cultural Heritage Visual Narrative Approaches for Public Health Education

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ABSTRACT

Purpose: Public awareness of fluoride, particularly regarding its presence and effects in cultural heritage and broader contexts, remains low. Digital communication is an increasingly vital approach for preserving, disseminating, and providing access to cultural heritage.

Methods: This study develops an intangible cultural heritage visual narrative framework based on the digital communication of cultural heritage. Through the integration of multimodal technologies and immersive interactive design, it achieves accurate communication of fluoride knowledge.

Results: The technical approach centered on 3D laser scanning, hyperspectral imaging, and multispectral analysis, models intangible cultural heritage items involving fluoride craftsmanship. Combining this with a database of material composition spectra, a digital correlation model is developed. This study significantly improves users' depth of process understanding (mean score of 4.26/5), average health risk identification accuracy (90.2%), and average knowledge retention (77.2%), while also promoting long-term health behavior change.

Conclusions: Digital communication of cultural heritage can serve as an innovative tool for public health education, enhancing the comprehensibility of scientific knowledge and its effectiveness in behavioral transformation through cultural context.

Keywords: *Intangible cultural heritage; Visual narrative; Public health awareness; Fluoride cognitive media; Digital communication*

INTRODUCTION

In the field of global public health, a group of researchers are committed to exploring effective ways to improve public health cognition and behavior from different perspectives. The impact of insufficient sleep and sleep disorders on health, as well as the status of sleep health in the current public health agenda, and explored the necessity of incorporating sleep health into the public health agenda.[1] The combination of theoretical and practical research to sort out and define the concepts of health education, health promotion and public health, and analyzed the connections and differences between them.[2] Krasna and Fried[3] explored the reasons for the poor connection between public health education and government public health work, and proposed corresponding improvement measures. Investigated and analyzed the employment status, job needs and the latest development trends in the field of public health of graduates of Master of Public Health, evaluated the shortcomings of the existing Master of Public Health education courses, and put forward improvement suggestions.[4] In some areas, the training resources for community health workers are limited, and virtual public health education modules, as an emerging training applications, have the advantages of low cost and high accessibility. Constructed a conceptual framework to explain the various links of virtual public health education modules in the process of training community health workers.[5]

Auld et al.[6] reviewed and analyzed the work of the Public Health Education and Health Promotion Department of the American Public Health Association (APHA) over the past 100 years. Behavioral "nudge" strategies can effectively improve the participation and learning outcomes of public health graduate students in course content.[7] The current status and challenges of sex education in the United States after the overturning and analyzed the impact of this on public health education, and proposed corresponding response strategies.[8] The characteristics and trends of the Public Health 3.0 era, and combined with the current status of public health education, explored the reforms and adjustments that need to be made in public health education in terms of curriculum setting, teaching methods, and teacher team building.[9] The construction of mathematical model to simulate the impact of vaccination, treatment, and public health education on the spread of norovirus disease. Through mathematical analysis and computer simulation, they studied the control effect of different combinations of measures on the spread of norovirus disease.[10]

Although research has made progress in various aspects of public health education, the potential of digital cultural heritage communication in enhancing public health awareness remains underexplored. This paper applied the digital communication of cultural heritage as a medium for fluoride (F) awareness through intangible cultural heritage visual narrative method, aims to provide a new perspective and practical path for public health education. By analyzing the characteristics and advantages of digital cultural heritage communication and its application in fluoride awareness, this paper provides theoretical support and practical guidance for innovative practices in public health education, promoting the diversification and effectiveness of public health education.[11,12]

The present article constructs a framework that integrates visual narratives of intangible cultural heritage crafts with public health education, and designs a coupled model to transform the physical and chemical parameters of F into interactive, dynamic visual elements. It also develops an immersive narrative system based on augmented reality (AR) to achieve a cross-scale knowledge mapping from intangible cultural heritage crafts to human metabolic pathways. Through randomized controlled trials and physiological signal monitoring, it quantifies the effectiveness of this model in improving public cognitive efficacy and behavioral change, providing data-driven optimization strategies for public health education.

METHODOLOGY

Intangible cultural heritage visual narrative framework and technical path

The visual narrative framework constructed in this study aims to bridge the transition from the physical form of cultural heritage to the scientific knowledge about F contained therein, and then to public health awareness.[13,14] Its core is a ‘three-stage coupling’ model that systematically organizes the entire process from data foundation to end-user experience. The first stage is ‘scientific data visualization’, whose task is to transform abstract, invisible scientific parameters, such as mineral composition, thermodynamic curves, and spectral characteristics into intuitive graphics, images, and animations, preparing the raw materials for the narrative. Table 1 shows the F characteristics in five typical intangible cultural heritage crafts.[15]

The distribution of F content in minerals can be modeled by spatial interpolation functions as per equation 1.

$$C(x,y,z)=\sum_{i=1}^{n} w_i \cdot f_i(x,y,z) \tag{1}$$

C(x,y,z) refers to the F concentration of the three-dimensional (3D) coordinate point (x,y,z); w_i is the weight coefficient, f_i basis function and n the total number of sampling points involved in the interpolation.

Table 1. The summary of intangible cultural heritage crafts fluoride parameters

ICH craft type	Initial F concentration (mg/kg)	Diffusion coefficient ($\times10^{-9}$ m²s-1)	Reaction rate constant ($\times10^{-3}$ s^{-1})	Visualization effectiveness score (1-5)
Jingdezhen blue-and-white glaze	320	2.5	1.8	4.5
Longquan sword quenching molten salt	1050	4.2	3.5	4.8
Yixing zisha clay	180	1.1	0.6	4.0
Miao silver ornament treatment agent	650	3.0	2.4	4.2
Huizhou Inkstick raw mineral powder	420	2.0	1.5	4.3

Table 2. Hyperspectral characteristics of fluorine-containing mineral raw materials

Compound name	Chemical formula	Characteristic absorption peak wavelength (nm)	Average Reflectance (%)	Characteristic spectral range (nm)
Fluorite	CaF_2	780, 950	22.5	750-1100
Fluorapatite	$Ca_5(PO_4)_3F$	810, 1040	18.3	800-1100
Cryolite	Na_3AlF_6	860, 990	15.8	850-1050
Sellaite	MgF_2	740, 910	20.1	720-980
Elpasolite (reference example)	Na_3LiFeF_8 (simplified)	890, 1070	16.5	880-1120

The second stage is the process scene reconstruction, which uses digital technology to perform high-fidelity 3D restoration of representative projects of intangible cultural heritage, such as Jingdezhen blue and white porcelain firing and Longquan sword forging, and reconstruct their key process flows, providing a real and culturally rich spatial stage for the presentation of scientific data. The third stage is the health impact association, which aims to build a bridge between traditional crafts and modern scientific cognition, and dynamically associate the role of F in the process with its metabolic pathways in the human body and health effects, i.e., caries prevention and F poisoning.[16,17] The diffusion dynamics of F ions in the glaze sintering process can be described by the following equation (2).

$$\frac{\partial\varphi}{\partial t_1}=D\nabla^2\varphi-k\varphi \tag{2}$$

φ is the F ion concentration; D is the diffusion coefficient; k is the reaction rate constant; t_1 is the sintering time.

Multimodal data acquisition and digital modeling

To achieve the framework objectives, the study relies on cutting-edge multimodal technologies for data acquisition and knowledge modeling. The construction of the data layer begins with the digital archiving of intangible cultural heritage objects and scenes, and uses 3D laser scanning technology to obtain millimeter-level precision geometric models of the object's shape and surface texture, thereby providing a real digital foundation for subsequent interactive display. Hyperspectral imaging technology is used to capture the spectral information of each pixel on the surface of the object, which makes it possible to identify and map the chemical composition distribution of the surface material, providing data dimensions for visual analysis by the equation (3).

$$I(a,b,\lambda)=R(a,b,\lambda)\cdot E(\lambda) \tag{3}$$

$I(a,b,\lambda)$ is the radiation intensity of pixel (a,b) at wavelength λ; (a,b,λ) is the surface reflectivity; $E(\lambda)$ is the spectral power distribution of the incident light.

Through hyperspectral scanning of intangible cultural heritage fluorine-containing materials, their key optical characteristic parameters are obtained (Table 2).

At the knowledge level, a spectral database is established, which includes the standard absorption and emission spectral characteristics of more than 100 fluorine-containing mineral raw materials, including fluorapatite and fluorite, as a library for identifying and authenticating fluorine-containing components in intangible cultural heritage items. Computational materials science approaches are further introduced, and thermodynamic simulation software is used to simulate the reaction and volatilization behavior of F under specific process conditions to generate its kinetic curve. The volatilization rate of F can be modeled as given equation (4).

$$\frac{dY}{dt_2}=A\cdot e^{-E_a/RT}\cdot P_F \tag{4}$$

Y is the number of moles of F; A is the pre-exponential factor; E_a is the activation energy; R is the ideal gas constant (8.314 $J\cdot mol^{-1}\cdot K^{-1}$); T is the absolute temperature; P_F is the fluorine partial pressure; t_2 is the volatilization time. Finally, all data are integrated to construct a digital correlation model to reveal how a certain process step affects the performance and characteristics of the product through chemical behavior of a specific fluorine-containing raw material, forming a structured knowledge system that can be used for narrative.

Development of Immersive Visual Narrative System

Based on the digital model, an immersive visual narrative system based on mobile augmented reality technology is developed as the core interactive medium for conveying knowledge to the public. The system uses Unity 3D as the core development engine and integrates the Vuforia AR framework to achieve the superposition and interaction of virtual content and the real world. Its narrative structure is designed into three modules with gradually deepening layers, such as process deconstruction, ingredient traceability and health impact. Users can trigger the AR experience by simply scanning the intangible cultural heritage objects or specific image tags with their mobile devices. The first layer uses automatically played high-precision 3D animations to intuitively

Table 3. AR system performance parameters

Narrative module	Model face count ($\times 10^4$)	Rendering latency (ms)	Interaction response time (ms)
Process deconstruction	42.5	12.3	85±7
Component tracing	68.3	18.7	120±9
Health impact	35.8	15.2	95±8
System average	48.9	15.4	100±8

demonstrate key processes, such as the flow of molten salt covering the sword body when the sword is quenched in calcium fluoride molten salt, transforming abstract processes into visual dynamics. Its fluid dynamics simulation uses the Navier-Stokes equation (5).

$$\rho\left(\frac{\partial v}{\partial t_3}+v\cdot\nabla v\right)=-\nabla p+\mu\nabla^2 v+\rho g \qquad (5)$$

ρ is the molten salt density; v is the velocity field; p is the pressure; μ is the dynamic viscosity; g is the acceleration of gravity; t_3 is the quenching time.

The second layer allows users to interactively superimpose the microscopic structure model of the minerals contained in the object on the object, such as the fluorapatite crystals suspended on the glaze of blue and white porcelain and their X-ray diffraction patterns, to achieve penetrating observation from macro to micro. The third layer goes beyond the process itself and visualizes the absorption, distribution, and deposition of F ions in the human body in the form of dynamic heat maps, closely linking the components of traditional processes with modern medical health knowledge.[18,19] Table 3 shows the interaction indicators of each system module.

This layered and progressive narrative strategy empowers users to explore independently, guiding them along the logical chain of ‘what-why-what impact’, completing the in-depth construction from perceptual cognition to rational understanding.[20,21]

Optimization based on user physiological feedback

To ensure that high-precision models and complex narratives can effectively translate into accurate user cognition, this study introduces a user feedback mechanism based on physiological signals to quantitatively evaluate and optimize system design.[22,23] Using a commercial-grade wireless EEG headset, users simultaneously collect eye movement and EEG data while experiencing the narrative content. Eye tracking is used to capture the distribution of users' visual attention. By analyzing gaze heat maps and differences in dwell time on different information elements, it is possible to objectively assess which parts of the narrative content attract the most attention and which key information may be overlooked or cause confusion. The synchronously recorded EEG signals provide a window into the user's cognitive load and emotional engagement. The frequency domain feature extraction uses short-time Fourier transform.[24,25]

$$X(f,t)=\int_{-\infty}^{\infty} x(\tau)w(\tau-t)e^{-j2\pi f\tau}d\tau \qquad (6)$$

X(f,t) refers to the energy density represented in the time-frequency domain; x(τ) refers to the time domain waveform of the original EEG signal; w(τ-t) is the time domain window function; τ is the integral time variable; f is the analysis frequency.

By analyzing the power changes in frequency bands, such as α-waves and β-waves, it is inferred whether the user is in a state of relaxation and concentration, active thinking, or facing difficulties and pressure when processing information.[26]

EEG power analysis shows that the α-band power is highest in the health impact module (14.2 μV^2), significantly higher than the ingredient tracing module (9.8 μV^2), indicating that users are in a more relaxed and focused state when receiving health-related knowledge. Β-band power peaks in the ingredient tracing module (11.6 μV^2), indicating that the abstract information contained in this module, such as the microstructure of mineral components, requires greater cognitive effort and thinking (Figure 1a).[27,28]

Eye movement indicators exhibit complementary characteristics, such as the ingredient tracing module elicits the longest average fixation duration (480 ms) and the largest pupil diameter change (6.8%). Combined with its high β wave power, these indicators indicate that this module requires a high level of cognitive resource investment, stemming from the user's need to comprehend component information across scales (from macroscopic artifacts to microscopic crystals). Conversely, the health impact module, while exhibiting a shorter fixation duration (290 ms), coupled with its high α wave power, suggests that users can more efficiently process health information presented in the form of heat maps, demonstrating the effectiveness of visual metaphors in simplifying complex physiological processes. The process deconstruction module's eye movement indicators are intermediate, consistent with its moderate cognitive load (Figure 1b).

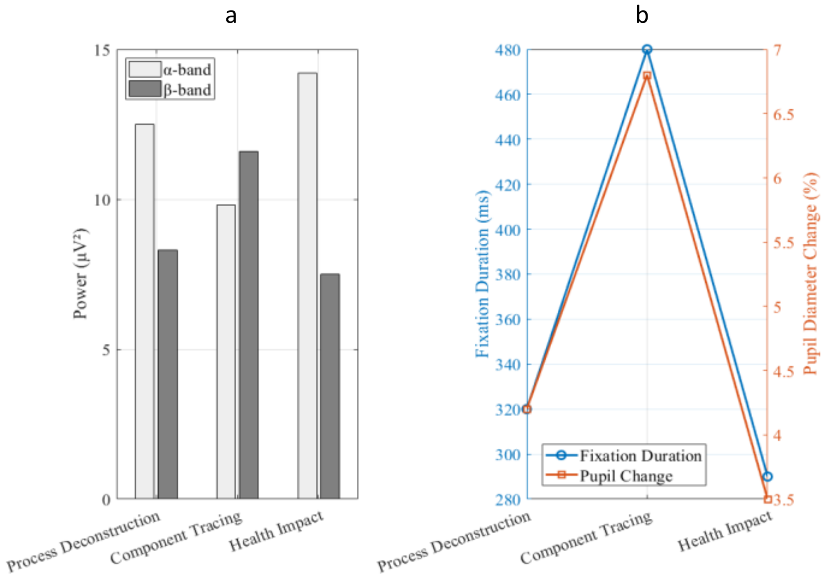

Figure 1. Physiological feedback information based on the EEG (a) and eye tracking (b)

By analyzing physiological data, cognitive bottlenecks or sources of deviation in the narrative process are identified, allowing for data-driven, iterative optimization of the layout of visual elements, the rhythm of presentation order, and the complexity of interaction logic, ultimately maximizing information transmission efficiency and user comprehension accuracy.[29,30]

RESULTS AND DISCUSSION

Experimental design and implementation

This study conducts an eight-week randomized controlled trial at six intangible cultural heritage sites in Jiangxi and Zhejiang provinces, China to evaluate the effectiveness of a digital cultural heritage communication system as a medium for public health education on F awareness. Participants are randomly assigned to either an experimental or control group. The experimental group uses a digital narrative system developed in this study, which includes a mobile augmented reality (AR) interactive manual and an immersive digital display wall. The control group uses traditional graphic display boards as learning materials.

Cognitive effectiveness enhancement

Twenty-four participants are recruited and randomly assigned to either the experimental or control group. The intervention is conducted using either the mobile augmented reality-based intangible cultural heritage visual narrative system or the traditional graphic display boards, respectively. Pre-tests, immediate post-tests, and a four-week delayed post-test are used to collect and quantify performance data for the two groups on three dimensions like depth of process understanding, accuracy in identifying health risks, and knowledge retention. The multi-dimensional effectiveness comparison results are shown in Figure 2.

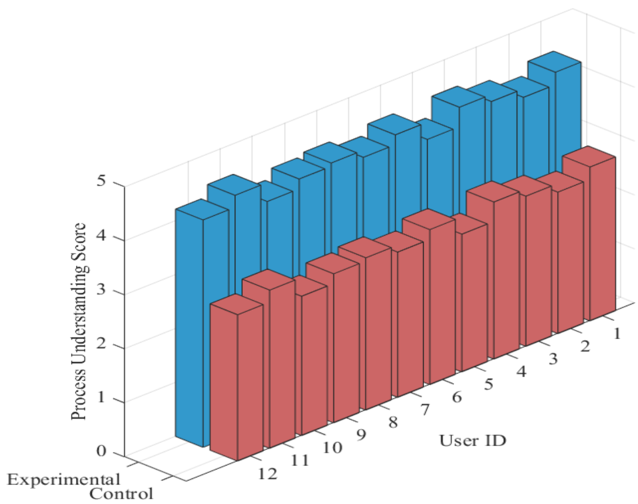

Figure 2. Depth of process understanding

Based on the above data, analysis shows that the experimental group generally outperforms the control group in terms of depth of process understanding, with scores ranging from 4.05 to 4.43, with an average of 4.26. The control group's scores range from 2.55 to 2.93, with an average of 2.76. In the three-dimensional bar chart, the experimental group significantly outperforms the control group overall, with users 4 and 11 performing particularly well. This demonstrates the clear advantages of the visual narrative system in conveying complex process knowledge and effectively fosters a deeper understanding of fluorine-containing processes within intangible cultural heritage. This confirms the role of digital media in ensuring consistent and reliable knowledge transfer.

The results of health risk identification accuracy shows that the experimental group achieves an average accuracy significantly higher (90.2%) than control group's (65.6%). The experimental group's data distribution is more concentrated (87.3-92.7%), demonstrating strong stability. The control group's data distribution is more dispersed (61.7-69.2%), further demonstrating the significant uncertainty in the effectiveness of traditional methods in knowledge transfer. The experimental group's scatter plots are primarily distributed in high-accuracy areas, while the control group's are concentrated in low-accuracy areas. The connecting line shows a significant upward trend, indicating that users' recognition ability improved after the digital intervention (Figure 3). This result highlights the potential of immersive visual storytelling in transforming abstract health knowledge. By dynamically linking the process effects of F with human health effects, it helps users establish cross-domain cognitive connections, thereby improving their ability to discern F-related health risks.

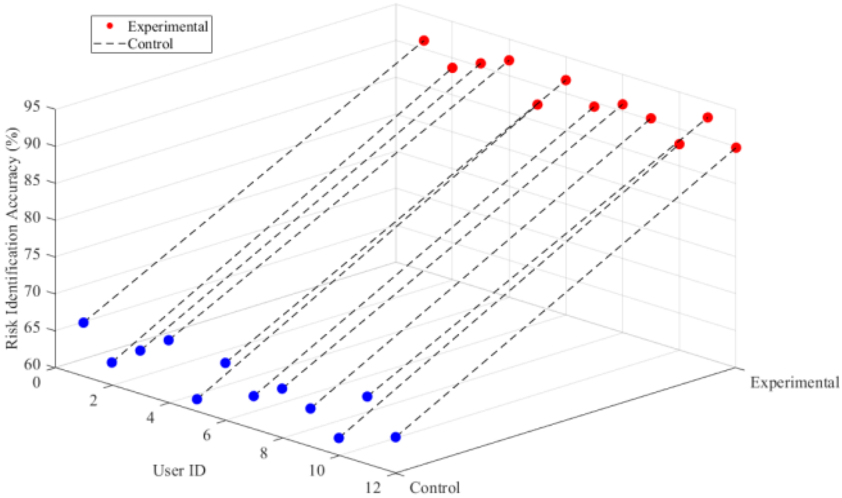

Figure 3. Impact of health risk identification accuracy

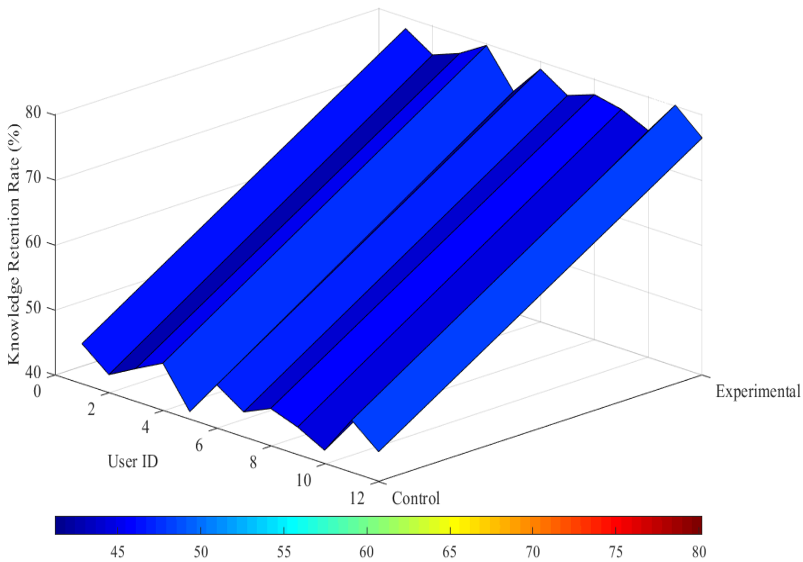

Figure 4. Impact of knowledge retention rate

A comparison of knowledge retention rates shows that the experimental group's average retention rate in the four-week delayed post-test significantly higher (77.2%) than control group's (44.8%). The experimental group's surface is generally positioned high in the 3D plot, indicating slow forgetting and sustained retention. The surface morphology further reveals that the experimental group's retention rate fluctuates less across users and exhibits high surface smoothness, indicating that the digital storytelling system produces a relatively consistent long-term knowledge retention effect for all participants. The control group's surface exhibits significant low-level fluctuations, reflecting the limitations of traditional educational methods in forming long-term memories. The results show that digital learning based on multimodal interaction and contextual reconstruction not only improves immediate cognitive outcomes but also effectively promotes long-term retention of knowledge by enhancing encoding depth and contextual relevance, providing a technical path for the sustained effectiveness of public health education (Figure 4).

Long-term behavior change tracking

A 12-week behavioral tracking experiment is conducted in addition to the immediate post-test (4 weeks). The testing process is as follows:

Oral hygiene log: Daily record of F toothpaste use frequency (≥2 times/day counted as effective use) and brushing duration per session (≥2 minutes counted as meeting the standard).

Clinic visit verification: Dental visit records are synchronized with the electronic health card (preventive cleaning/ F application treatment counted as effective visits). The F-tracking results are shown in Table 4.

Fluoride toothpaste usage remains high at 92.7% over the 12-week period, a 24.4% increase compared to the control group. The experimental group also meets public health guidelines for daily tooth brushing compliance (85.1%) and dental visit frequency (1.8 times/12 weeks). The control group's behavioral indicators showed a continued decline, reflecting the limitations of traditional education methods in reinforcing behavior. This demonstrates that intangible cultural heritage visual narratives strengthen the sustainability of healthy behaviors through cultural identity. This enhanced behavioral stickiness across time and space reveals the value of digital cultural heritage media in facilitating the transformation from cognition to behavior to habit.

Cross-population applicability verification

The applicability of the cultural heritage digital communication system as a F awareness medium across different age groups are evaluated through cross-population testing design, resulting in the System Usability Scale (SUS) scores shown in Figure 5.

Table 4. The twelve-week health behavior analysis results

Indicator	Intervention group (12-week mean)	Control group (12-week mean)	Group difference (Δ)
F-toothpaste usage rate (%)	92.7	68.3	+24.4
Daily brushing compliance rate (%)	85.1	62.9	+22.2
Dental visit rate (times/12 weeks)	1.8	0.7	+1.1
Behavior adherence index (0-10 points)	8.6	5.3	+3.3

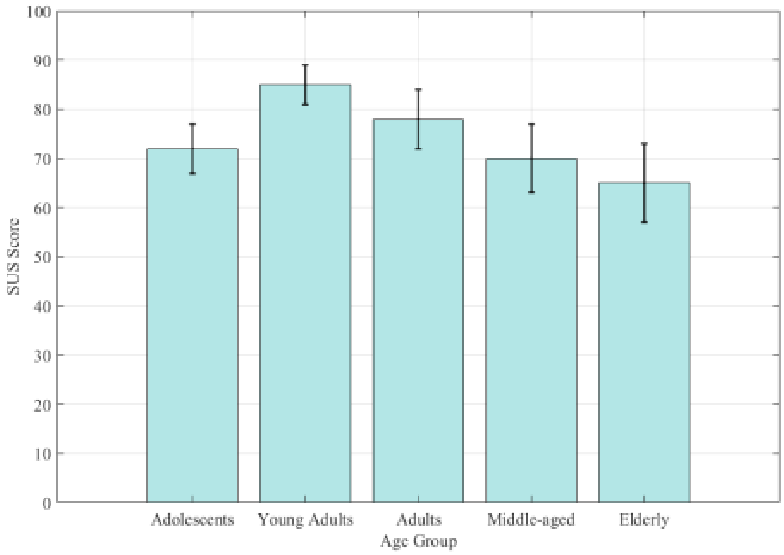

Figure 5. System usability scores for different age groups

The System Usability Scale (SUS) scores for different age groups showed a clear gradient. The young adult group has the highest score (85±4), significantly outperforming all other groups, while the elderly group has the lowest score (65±8). The adolescent (72±5), adult (78±6), and middle-aged groups (70±7) rank in the middle. The score distribution characteristics indicate significant correlation between system usability and age. Younger groups, due to their greater familiarity with digital technology, exhibit better system adaptability and operational experience. System usability performance shows a significant negative correlation with user age, indicating that the current system's interaction design, interface complexity, and learning curve are more aligned with the usage habits and cognitive patterns of young digital natives. To enhance the inclusiveness and accessibility of public health education programs, it is essential to implement dedicated, age-friendly design iterations for middle-aged and elderly users. This includes streamlining navigational hierarchies, optimizing visual contrast, providing multimodal interaction support (e.g., voice), and considering the introduction of progressive learning guidance mechanisms to bridge the digital divide and ensure that users of all ages can effectively utilize this digital medium to acquire F-related health information.

CONCLUSION

This study successfully addresses the challenges and difficult-to-understand F knowledge and low public adherence in public health education by constructing a visual narrative framework for the digital dissemination of cultural heritage. However, limitations remains that the system's applicability to the elderly population is limited, requiring further optimization of age-friendly design and it lacks coverage of the digital divide in remote areas. Future work can focus on interdisciplinary collaboration, deepening AI dynamic narratives and personalized recommendation algorithms, and promoting public health education towards greater inclusiveness, precision, and cultural context.

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DISCLOSURE OF FINANCIAL AND NON-FINANCIAL RELATIONSHIPS AND ACTIVITIES AND CONFLICTS OF INTEREST

None

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