

Developing an XR-FRAME-based augmented reality app for industrial heritage in Chongqing



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ABSTRACT

Industrial heritage sites are important carriers of urban historical memory and technological progress. However, they often face low public engagement and limited understanding because conventional static display methods fail to effectively communicate their value. This challenge highlights the need for innovative approaches to revitalize these sites and improve visitor experiences. To address this issue, we conducted a stratified random experiment involving 90 participants divided into three groups. Each group explored a representative industrial heritage site in Chongqing using a different approach: a lightweight AR mini-program based on the XR-FRAME framework (integrating extended reality, fusion, feedback, evaluation, and management), web-based AR, or traditional guided tours. Data were collected using SDK tracking to monitor user interactions, eye tracking to analyze visual attention, a Likert scale to evaluate user experiences, and a knowledge post-test to assess learning outcomes. Analysis of variance showed that the XR-FRAME group significantly outperformed the other groups across multiple dimensions. It achieved higher scores in interactive behavior, indicating greater user engagement and participation; user experience, reflecting stronger immersion and emotional connection; and cognitive comprehension, demonstrating a better understanding of the site's technological and historical significance. These findings highlight the XR-FRAME framework's ability to effectively combine active participation, immersive experiences, and knowledge acquisition. This study contributes to cultural heritage communication by providing empirical evidence of the framework's effectiveness as a comprehensive and innovative approach for revitalizing industrial heritage in the digital age, with broader implications for improving public engagement and understanding of cultural heritage worldwide.

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1. Introduction

As an irreplaceable living fossil in the evolution of urban history, industrial heritage not only records the social production mode and technological innovation track of a specific era, but also carries the collective memory of a generation and the pulse of urban development. With the improvement of cultural protection awareness, the various values of industrial heritage are being rediscovered and valued. As one of the birthplaces of modern industry

in Southwest China, Chongqing has rich and unique industrial heritage resources: many military factories established during the Anti-Japanese War built industrial fortresses supported by the front line; During the three line construction period, it was a machinery manufacturing base cluster rising by virtue of its inland strategic position (Weng et al., 2024); As well as the wharf warehouse system along the Yangtze River, which witnessed the shipping and industrial prosperity. These sites scattered throughout the city are not only the key coordinates of Chongqing's spatial evolution, but also the specific link for people to contact China's industrialization process (Alzarrad et al., 2024; Chhabhaiya et al., 2026; Zimmermann et al., 2023).

However, at present, most of the industrial heritage faces multiple challenges: some of them are abandoned due to outdated functions, buildings and equipment are damaged by natural or human

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factors, and the public's awareness of its historical value is generally insufficient. In the trend of cultural tourism integration, many tourists still simply equate industrial sites with old factories or abandoned machinery, and fail to understand the technical logic, social significance and historical background behind them. This cognitive gap not only weakens the cultural influence of industrial heritage, but also makes the road of sustainable protection and revival full of hardships. Although the existing digital solutions, such as static online exhibition and basic multimedia exhibition, try to make up for the gap, the lack of interaction and immersion, the limitations of personalized or situational information, especially the problem of failing to make full use of emerging technologies such as AR to create dynamic multi-sensory experience, make them unable to fully demonstrate the vitality of industrial heritage.

The rise of augmented reality (AR) technology provides an innovative solution to this communication problem (Noh et al., 2009; Sahli and Lichy, 2026). This technology can accurately overlay virtual historical information and scene images on the real heritage space, reconstruct the past production environment through visualization and build interactive narrative, so that the abstract historical context becomes concrete and easy to understand. AR enables tourists to have a clearer understanding of the value of industrial heritage, significantly deepen their experience, and inject new vitality into its revival. XR-FRAME (based on the experience model of factory ruins in augmented reality) is a system design framework integrating XR technology, integration, feedback, evaluation and management, which has been increasingly widely used in the field of cultural heritage display. The framework emphasizes the user centered immersive experience, pays attention to the dynamic coordination and multimodal interaction between virtual and real content, and can activate its education and cultural communication functions while retaining the authenticity of the site. The system uses 3D modeling, GIS positioning, voice commentary and interactive animation technologies, and automatically activates the historical scene when tourists approach the heritage site - such as rebuilding the production line, telling the story of key figures or simulating the development process of historical events.

BeiCang Industrial Heritage Park, located in the downtown of Jiangbei District, Chongqing, is such a model. It has changed from an old warehouse to a cultural and tourism landmark, becoming a cultural oasis in the city. BeiCang witnessed the historical memory of Chongqing textile industry. Through the urban renewal mode of "protection texture + function update," BeiCang became the model of industrial heritage activation and utilization, and won the first batch of national tourism and leisure blocks and many other honors. The renovation project launched after 2010 completely changed the fate of BeiCang, following the concept of respecting

history and retaining the original characteristics, avoiding large-scale demolition, and only carrying out necessary repairs to the facade, while carefully preserving industrial elements such as the Soviet style factory roof. The version 2 transformation plan launched in 2022 was expanded to 130,000 square meters, covering 44 buildings and 72 residential units. It successfully integrated the industrial heritage and contemporary community life. It not only retained the daily living environment of local residents, but also organically embedded the cultural and creative industries in the living space, forming a cultural asset network embedded in the urban fabric. Now, BeiCang has developed into a diversified and comprehensive cultural industry cluster, combining the rough industrial design with modern exquisite aesthetics, breaking the static display mode of traditional industrial sites. Through the combination of aesthetics, daily life and interdisciplinary forms, it closely links historical buildings and modern urban life. Through the XR-FRAME framework, BeiCang not only realized the rebirth of physical space, but also opened up a new path for the integration of technology and cultural space, providing a replicable experience for the activation and utilization of industrial heritage. This not only strengthens the effectiveness of XR-FRAME as an industrial heritage revitalization tool, but also provides valuable insights for the field of cultural tourism and education technology.

This research aims to evaluate the cognitive and emotional impact of the AR prototype on users' understanding of industrial heritage symbols.

2. Literature review

Extended reality technology integrates Augmented Reality, Virtual Reality, and Mixed Reality, reshaping industrial heritage interpretation by transforming abstract historical information into dynamic, real-world-overlaid content through 3D modeling and spatial positioning (Oh et al., 2009). It is crucial to clarify that XR-FRAME is an official XR/3D application solution provided by mini-program platforms, which is implemented based on a hybrid scheme. This inherent attribute endows it with prominent advantages: performance close to native applications, excellent display effects, high ease of use, strong expandability, and a progressive development model, while fully complying with mini-program development standards. Built on this official solution, the XR-FRAME framework integrates four core modules - integration, feedback, evaluation, and management to form a closed-loop system for industrial heritage experience optimization (Yoon et al., 2012). Yet its specific technical implementation remains under-elaborated, leading to reproduction difficulties that limit its practical value in digital revitalization. To address this research gap, the specific composition of each module in terms of algorithms, software tools, and design patterns is clarified in detail: the integration module, responsible for seamless virtual-real

connection, adopts spatial positioning algorithms such as ARKit and ARCore, uses Blender and 3ds Max for 3D modeling of industrial heritage sites and relics, and relies on Unity engine for real-time rendering to achieve dynamic overlay of virtual content and real scenes (Matin and Mangina, 2025), following a user-centered design pattern to ensure the natural integration of technology and cultural content. The feedback module is supported by user behavior analysis algorithms including random forest and support vector machine, collects data through OpenCV-based facial expression recognition tools and interactive behavior recording plugins, and adopts an iterative design pattern to dynamically adjust content display strategies based on real-time feedback. The evaluation module uses cognitive load measurement algorithms and engagement score calculation models, matches with data analysis tools such as SPSS and Python's Pandas library for quantitative analysis, and follows a goal-oriented design pattern to ensure evaluation indicators are closely linked to heritage experience effectiveness (Iftikhar et al., 2023). The management module relies on database management tools such as MySQL for user data and content resource storage, adopts a modular design pattern to facilitate function expansion and maintenance, and uses lightweight deployment tools to ensure the stable operation of the entire framework in AR mini-programs - consistent with the strong expandability and progressive characteristics of the official XR-FRAME solution (Christopoulos et al., 2020).

AR mini-programs, as lightweight XR applications, offer high accessibility and low thresholds, making them suitable for industrial heritage mobile tourism. Their primary functions include location-based tours, 3D artifact integration, interactive timeline navigation, and contextual storytelling. Unlike high-investment specialized XR equipment, they operate on ordinary mobile devices without additional hardware or APP downloads, effectively expanding public participation - especially among young groups (Hong et al., 2021). Through immersive storytelling, they achieve embodied cognition of industrial heritage, and social sharing functions further amplify heritage impact, as verified in relevant digital projects.

Chongqing, a birthplace of modern industry in Southwest China, boasts rich industrial heritage formed during the War of Resistance Against Japan and Third Front Construction, including military factories, machinery bases, and wharf facilities. These sites document the nation's wartime struggle, industrial development, and workers' spirit, while reinforcing Chongqing's dual identity as a river and industrial city. However, rapid urbanization has brought significant challenges: most sites remain in static exhibition phases, with bland text-based interpretation systems that fail to attract public attention. Over-commercialization, exemplified by Eling No. 2 Factory, obscures industrial history and dilutes heritage value. Relevant research highlights the need to balance protection with experience

innovation, and public welfare with commercialization (Lamers and Lanen, 2021).

Digital transformation is urgent to address these issues, with XR/AR regarded as key tools for immersive heritage interpretation. XR breaks time and space constraints, transforming abstract history into intuitive audiovisual content that allows visitors to engage with historical scenes and equipment. This study takes Chongqing Beicang Industrial Heritage Park as a case, developing an XR-FRAME-based AR mini-program to clarify the framework's technical implementation and solve reproducibility problems - an effort that fully leverages the advantages of XR-FRAME as an official mini-program solution, such as its compliance with mini-program development standards, high ease of use, and strong expandability. Specifically, this study refines the algorithm selection, software matching, and design pattern application of each XR-FRAME module in combination with the park's industrial heritage characteristics, while adhering to the progressive development model of the official solution to ensure the mini-program is easy to develop, debug, and promote. For example, the integration module's 3D modeling of old factory buildings and production equipment uses Blender for precision modeling and Unity's PhysX physics engine for basic physics simulation to ensure the consistency of virtual models with real relics, while the spatial positioning algorithm is optimized based on the park's complex indoor and outdoor environments to avoid positioning deviation - taking advantage of XR-FRAME's native-level performance to ensure smooth real-time rendering (Teh et al., 2024). The feedback module's behavior analysis algorithm is adjusted to focus on collecting user interaction duration and task completion data for industrial heritage content, and the iterative design pattern is used to continuously optimize digital human narration and interactive task settings based on user feedback, which is highly compatible with the progressive and expandable features of the official XR-FRAME solution. The AR mini-program incorporates interactive digital humans and scenario-based guidance to enhance immersion, moving beyond basic static information display to active exploration, all based on the clear technical implementation of the XR-FRAME framework and the inherent advantages of its official mini-program solution (Ierache et al., 2018).

Basic AR applications in industrial heritage sites are monotonous, forcing passive information consumption and failing to spark curiosity. In contrast, the XR-FRAME-based version uses digital humans aligned with Chongqing's industrial context to deliver scene-specific narration, explaining factory structures and simulating production workflows. Scenario-based guidance and interactive tasks further deepen engagement and knowledge retention, consistent with game-based AR experience models. This study will verify AR's effectiveness by comparing data from users of the XR-FRAME-based mini-program and those using

traditional static displays. Clarifying XR-FRAME's technical details - including the specific algorithms, software tools, and design patterns of each module - will enable its reproduction and promotion across more industrial heritage sites, which is further supported by its nature as an official mini-program XR/3D solution. The modular design pattern adopted by the management module, for instance, is highly consistent with the strong expandability of the official XR-FRAME solution, allowing different industrial heritage sites to adjust software tools and algorithm parameters according to their own characteristics without modifying the overall framework structure: for wharf heritage sites, the integration module can replace 3D modeling tools with more specialized marine engineering modeling software, while the feedback module can optimize data collection algorithms to focus on user interest in shipping history. Meanwhile, its compliance with mini-program development standards and high ease of use significantly reduces the development and deployment threshold for relevant projects, making the framework more accessible to researchers and practitioners.

This replicable paradigm will provide a clear technical reference for industrial heritage protection globally, ensuring heritage conveys its historical, technological, and spiritual value, and boosting Chongqing's urban cultural construction. Notably,

the selection of all algorithms and software tools in the XR-FRAME framework adheres to the principle of accessibility and practicality, avoiding overly complex and high-cost technical solutions - consistent with both the low-threshold application characteristics of AR mini-programs and the ease of use and progressive development model of the official XR-FRAME solution, which further enhances the framework's reproducibility and promotion value (Capuano et al., 2016).

To visually demonstrate the advantages of XR-FRAME-based AR in practical application, Fig. 1 presents a comparison of AR technology in Chongqing Industrial Park, showing that XR-FRAME versions have significantly clearer visual richness and more intuitive prompts. Table 1 compares web-based augmented reality (AR) and the XR-FRAME framework in terms of performance, interaction, development, user acquisition, and resource loading. Table 2 summarizes the theoretical foundations and relevant case studies of XR-FRAME, highlighting the applications of augmented reality and other digital technologies in industrial heritage preservation, renovation, and cultural tourism. Table 3 presents the industrial heritage AR cultural communication technology routes based on the XR-FRAME framework, outlining the technical foundation, core framework components, application practices, and cultural communication outcomes.

Table 1: Comparison of XR-FRAME and browser-based augmented reality

No.	Dimension	XR-FRAME (WeChat mini-program): advantages	Browser-based AR: advantages	Reported disadvantages of browser-based AR
1	Performance	High frame rate, low latency, real-time rendering	Not provided in the supplied table	Web AR is prone to lag in complex scenes
2	Interaction	Highly immersive, multimodal AI interactive digital human	Basic interaction, browser available	Web AR interactive experience is limited
3	Development	Integrated tool chain and WeChat ecological capabilities	Flexible and free	Web AR development costs are high and debugging is difficult
4	User acquisition	Direct access, sharing, and payment within the WeChat ecosystem	Cross-platform access	Web AR conversion and retention are low
5	Resource	Local cache, fast loading	Flexible network loading	Web AR loading is affected by network speed

Table 2: Theoretical foundations and related cases

No.	Topic/role in the study	Case study or technology	Description and relevance
1	Theoretical basis of the XR-FRAME framework	References	Includes applications of VR and AR in cultural heritage protection, display, and tourism, drawing on reviews of augmented reality (Azuma, 1997) and AR, VR, and MR in cultural heritage (Bekele et al., 2018).
2	Immersive experience with AR technology	Shanghai Yangpu Riverside Renovation Project	Through digital technology, abandoned factories are transformed into immersive experience centers, allowing visitors to experience the industrial production scenes of the past.
3	Industrial heritage digital-renovation technology system	A heavy industrial plant renovation project	Data layer: Data collection using the FARO Focus S350 3D laser scanner and the DJI Matrice 300 RTK drone; Analysis layer: Structural safety assessment based on the Mask R-CNN crack recognition model and finite element analysis (FEA); Implementation layer: Precision robotic construction based on BIM model path planning
4	Industrial-heritage cultural-tourism complex	Shanghai Yangpu Riverside	By introducing digital technologies such as VR, AR, AI and IoT, industrial heritage has been given new life, and visitors can gain a deeper understanding of the historical and cultural background of industrial heritage through immersive experiences.
5	Analysis of cultural-heritage XR tourism demand	TripAdvisor and AirPano user reviews	Researchers crawled 22,000 real user reviews from the travel guide website TripAdvisor and the virtual tour website AirPano and conducted text mining on them, extracting six themes, revealing the six major uses of XR technology in cultural heritage tourism that tourists are most concerned about.

Table 4 summarizes the empirical studies in terms of data collection methods, measurement tools, and the corresponding research content. Table 5 compares the XR-FRAME-based AR mini-program, web-based AR, and traditional guided tours in terms of interaction, user experience, and knowledge acquisition. Fig. 2 illustrates the overall results for the three experimental groups across the dimensions of interactive behavior, experience,

and knowledge understanding, with Group A outperforming Groups B and C in all three dimensions.

3. Research methodology

Augmented Reality (AR), a key branch of Extended Reality (XR), has become a crucial medium

for disseminating cultural heritage due to its distinctive fusion of virtual and real elements. The XR-FRAME framework integrates five core modules

to create a closed-loop cultural tourism experience system.

Table 3: XR-FRAME technology route for industrial-heritage cultural communication

No.	Layer/hierarchy	Component or application	Main content/intended outcome
1	Technical foundation layer	AR technology (Azuma definition)	Augmented reality technology basics
		Extended reality (XR)	Virtual and real fusion features
2	XR-FRAME framework core layer	Theoretical support	Constructivism + multimodal learning
		Cultural heritage applications	Research results of Bekele et al. (2018)
		Data collection layer	High-precision point cloud model, spatial registration, and environmental perception
3	Application practice layer	Analysis layer	Structural safety assessment, historical state deduction, and content generation basis
		Implementation layer	BIM model planning, AR content rendering, virtual-reality matching
		Interactive experience layer	Immersive narrative, task-oriented interaction, emotional resonance
4	Cultural communication effect layer	Feedback evaluation layer	User behavior tracking, dynamic optimization, and personalized navigation
		Shanghai Yangpu riverside project	Abandoned textile factory digital museum, AR mini program interactive experience
		Chongqing industrial heritage scene	Restore the military production process and lower the threshold for understanding
5		Heavy industrial plant renovation	Digital restoration path, high-fidelity data foundation
		Reshaping cognitive pathways	Breaking the time barrier
		Participatory cultural production	Co-creation of meaning
6		Embodied participation experience	Emotional investment
		Social network communication	One-click sharing

Drawing on [Azuma's \(1997\)](#) definition of AR technology and incorporating [Bekele et al.'s \(2018\)](#) comprehensive research on the application of AR, VR, and MR in cultural heritage, it reinforces the role of immersive experience in the construction of cultural cognition. In the context of industrial heritage, XR-FRAME uses high-precision spatial

registration and dynamic environmental perception to precisely match virtual historical scenes with existing industrial structures. Visitors can "see" lost production processes and the movements of historical figures in real space, breaking down time barriers and reconstructing the spatiotemporal dimensions of industrial memory.

Table 4: Summary of empirical methods and data collection

No.	Research content	Specific information	Source/reference label as supplied
1	Data collection methods	1. 3-coordinate measurement method, laser triangulation method, structured light method and computed tomography (CT) 2. After scanning the image, a large amount of point cloud data is obtained, including disordered point clouds, noisy point clouds and redundant point clouds	Data collection methods
2	User review data collection	1. We crawled 22,000 real user reviews from TripAdvisor and AirPano. 2. We used the Latent Dirichlet Allocation algorithm to perform topic modeling on the reviews.	User review data collection
3	Data collection and measurement tool development	1. Data were collected via a Google Forms survey. 2. The non-immersive VR (niVR) website Dubai360.com was selected as the research object. 3. A multi-item questionnaire was used, with responses adopting a seven-point Likert scale. 4. Specific measurement items included system quality (SYSQ), sense of presence (PRES), object-related authenticity (OBAU), activity-related authenticity (ACAU), and satisfaction (SAT).	Data collection and measurement tool development

Table 5: Comparison of reported outcomes across visitor-experience dimensions

No.	Dimension	What the dimension measures	XR-FRAME AR mini-program	Browser-based AR	Traditional guided tour
1	Interaction	The interactive experience between users and applications, such as ease of operation and response speed.	Significantly higher than browser-based AR and traditional guided tours	Lower than XR-FRAME	Lowest reported
2	User experience	The user's overall experience, including immersion, fun, etc.	Significantly higher than browser-based AR and traditional guided tours	Lower than XR-FRAME	Lowest reported
3	Knowledge interest and understanding	Users' interest in and understanding of Chongqing's industrial heritage cultural knowledge.	Significantly higher than browser-based AR and traditional guided tours	Lower than XR-FRAME	Lowest reported
4	Knowledge acquisition	The degree to which users have mastered Chongqing's industrial heritage cultural knowledge after learning through the AR mini-program.	Significantly higher than browser-based AR and traditional guided tours	Lower than XR-FRAME	Lowest reported

AR technology reshapes visitors' cognitive pathways and offers significant advantages in understanding complex technological heritage. For example, in the Shanghai Yangpu Riverside Redevelopment Project, an AR mini-program transformed an abandoned textile factory into an interactive digital museum. Visitors scanning factory components trigger animations, images, and sound effects, creating an immersive narrative. This aligns with constructivist theory, which encourages visitors to actively construct knowledge systems. Based on

multimodal learning theory, AR synergistically stimulates different cognitive areas of the brain, improving information encoding efficiency and memory retention. In Chongqing's industrial heritage setting, this technology can recreate military production processes, lowering the barrier to understanding for non-expert visitors.

The dissemination of industrial heritage culture faces challenges such as information fragmentation. The XR-FRAME framework addresses this challenge through a layered content architecture and dynamic

feedback mechanism. For example, in a digital renovation project involving a heavy industrial plant, the data acquisition layer constructs a high-precision point cloud model; the analysis layer assesses structural safety and deduces historical usage; and the implementation layer relies on BIM models to

plan restoration paths. This technological chain provides a high-fidelity data foundation for AR content generation. Furthermore, the feedback and evaluation module tracks user behavior in real time, dynamically optimizes information push strategies, and delivers personalized guided tours.

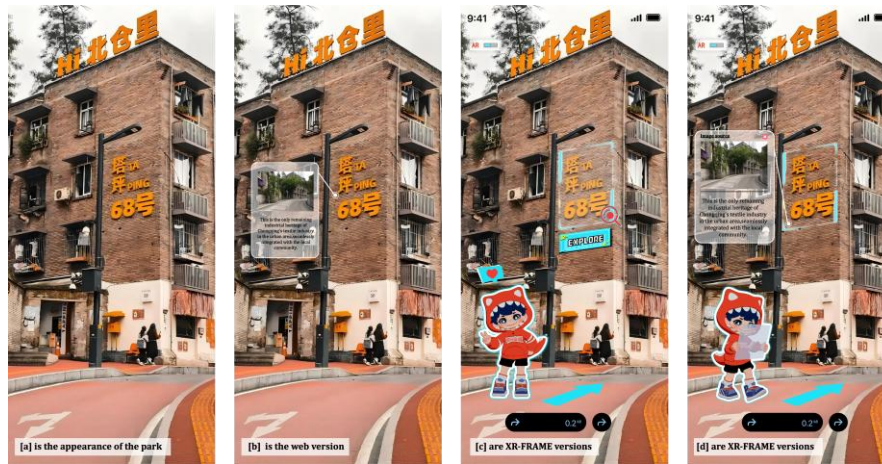


Fig. 1: Visual comparison of Beicang Industrial Heritage Park and the augmented reality (AR) implementations: (a) original site view; (b) browser-based Web AR interface; (c) XR-FRAME interface with a digital guide; and (d) XR-FRAME interface with contextual information

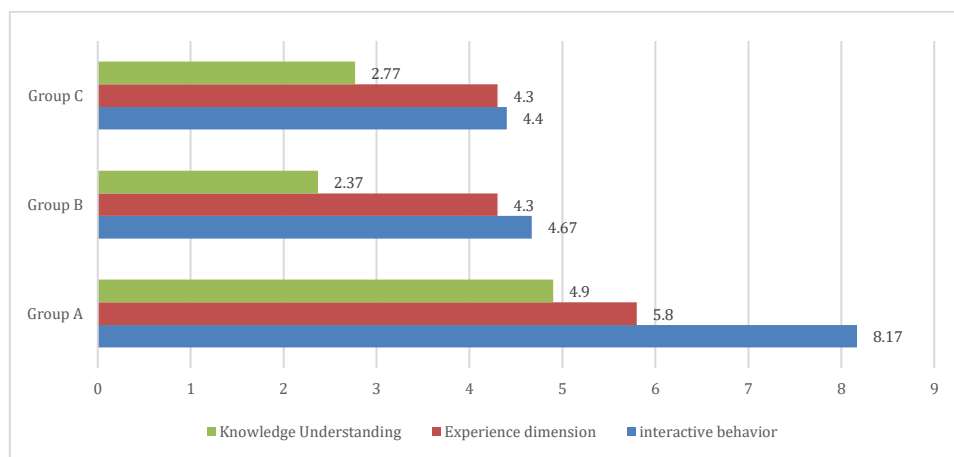


Fig. 2: Mean scores for interactive behavior, user experience, and knowledge understanding among Group A (XR-FRAME mini-program), Group B (browser-based Web AR), and Group C (traditional guided tour)

From a cultural communication perspective, AR mini-programs are platforms for participatory cultural production. Text mining of user reviews reveals six core needs for visitors' XR experiences of cultural heritage, including embodied participation and co-creation of meaning. The XR-FRAME framework integrates AR storytelling with contextual experience design, supporting task-oriented interactions and stimulating user emotional resonance and behavioral engagement. This framework also supports one-click sharing of AR content on social networks, promoting the dissemination of industrial heritage culture.

4. Results

This study systematically validated the effectiveness of the XR-FRAME framework in AR mini-programs through a comparative experimental design. We recruited 90 volunteers ($n = 90$) aged

between 18 and 45 through various channels to ensure a diverse and representative sample. 1. Online Platforms: We posted recruitment announcements on popular social media platforms such as WeChat, Weibo, and QQ groups. These announcements clearly outlined the study's objectives, age range, expected time commitment (a two-week experimental period), and the benefits of participation, such as firsthand experience with cutting-edge AR technology and a small monetary compensation. 2. University and College Outreach: We contacted local universities and colleges, particularly those offering programs in computer science, digital media, and design. We distributed flyers on campus, held information sessions in classrooms, and collaborated with student organizations to promote the study. This approach helped us reach young people in our target age group. 3. Community Centers and Local Organizations: We contacted community centers in

urban and suburban areas, as well as local cultural and technology-related organizations. By presenting and leaving recruitment materials, we attracted volunteers from diverse social backgrounds and varying levels of technological familiarity.

Stratification Criteria: The 90 volunteers were stratified based on three key factors: gender, educational background, and digital media usage habits. Gender was considered because it may influence users' interaction styles and preferences in AR environments. Educational background was categorized into three groups: high school or below, undergraduate, and graduate. This was based on the assumption that different educational levels may lead to different cognitive abilities and approaches to learning through AR. Digital media usage habits were categorized into three groups: low (less than 2 hours of digital media use per day), moderate (2-5 hours per day), and high (more than 5 hours per day). This factor is crucial because it influences users' comfort and proficiency with AR-related technologies.

Randomization Process: After stratification, volunteers within each stratum were randomly assigned to one of three groups (Group A, Group B, or Group C) using a computer-generated random number sequence. Specifically, each stratum was divided into three equal subsets according to the random number sequence, with each subset corresponding to one experimental group, ensuring that the distribution of gender, educational background, and digital media usage habits was consistent across the three groups. Chi-square tests for gender and educational level, and one-way ANOVA tests for age ($P > 0.05$) indicated no statistically significant differences in the randomized results, confirming the effectiveness of the stratified random assignment and eliminating potential confounding factors. Group A used a lightweight WeChat AR mini-program developed based on the XR-FRAME framework, supporting spatial anchoring, gesture interaction, and real-time feedback; Group B used a Web AR browser application that relied on image recognition to trigger content; and Group C used traditional graphic display boards and manual explanations. All three experiments were conducted at the same industrial heritage site to ensure consistent cultural context. The two-week experiment period allowed participants to experience only one guided tour method to avoid distractions. To measure the experimental outcomes quantitatively, two standardized psychological scales were adopted: the System Usability Scale (SUS) and the Igroup Presence Questionnaire (IPQ). The reliability and validity of both scales were verified in the context of this study to ensure the accuracy and stability of the measurement results. For the SUS, internal consistency reliability was tested using Cronbach's α coefficient, yielding a value of 0.82, which is above the recommended threshold of 0.7, indicating good internal consistency among the scale items. Construct validity was evaluated through exploratory factor analysis (EFA), which extracted a single factor explaining 68.3% of the total variance,

consistent with the one-dimensional structure of the SUS. For the IPQ, Cronbach's α coefficient was 0.87, demonstrating high internal consistency. Construct validity was also tested via exploratory factor analysis (EFA), which extracted three common factors (spatial presence, involvement, and realness) explaining 71.5% of the total variance, with all item loadings greater than 0.65, confirming that the IPQ has good construct validity in measuring the immersive presence of participants in the AR-based industrial heritage tour experience.

The AR mini-program deeply integrates the XR-FRAME framework: The XR layer accomplished virtual-real fusion reconstruction through high-precision 3D modeling and SLAM (Simultaneous Localization and Mapping) technology. The framework's Feedback mechanism monitored user behavior to dynamically adjust information flow, while the Evaluation phase quantified improvements in cognitive understanding through pre-/post-experiment questionnaires and context-specific questions. Meanwhile, the Management backend compiled operational data into user profiles. In contrast, Web AR - constrained by browser performance - relied solely on static model overlays and clickable pop-ups, severely limiting interactive scope. The Traditional group (Group C) followed a linear narrative without customized exploration routes, though all groups completed the same tasks of identifying industrial components, organizing timelines, and exploring cultural elements.

Data collection adopted a mixed-methods strategy: User interactions were tracked using SDK (Software Development Kit) tools to measure metrics such as click frequency, stay duration, and other action sequences, while heatmaps were used to visualize the distribution of user attention. The user experience was evaluated using the SUS (System Usability Scale) and the IPQ (Immersive Experience Questionnaire) Presence Scale, both employing a 5-point Likert rating system. To assess knowledge comprehension, pre-test and post-test assessments were conducted; the post-test included 10 multiple-choice questions and 2 open-ended short-answer questions, covering aspects such as factual recall, causal reasoning, and value interpretation. After the experiment, semi-structured interviews were conducted with 10 participants from each group to explore topics including sense of immersion, information overload, and emotional resonance. Following standardized data processing, one-way analysis of variance (ANOVA) was applied to test for differences between groups. Cohen's d was further used to calculate effect sizes, ensuring both the statistical validity and practical significance of the research conclusions.

5. Conclusions

In terms of interactive behavior, one-way ANOVA was conducted to examine differences across the three groups after thoroughly verifying test assumptions. The Shapiro-Wilk test confirmed

normal data distribution within each group (all p -values > 0.05), and Levene's test verified homogeneity of variances ($p = 0.163 > 0.05$). The one-way ANOVA revealed significant differences at the 0.01 level ($F = 27.555$, $p = 0.000$), and Tukey's HSD post-hoc test further indicated that the mean score of Group A (XR-FRAME) was significantly higher than those of Group B (WEB AR) and Group C (Traditional Guided Tour). At Beicang Industrial Park, Group A users leveraged the spatial interaction capabilities of XR-FRAME technology to overlay historical imagery onto textile warehouse walls via gesture control and interact with digital human guides through Q&A sessions, achieving an average of 8.2 interactions per exhibit with dwell time exceeding Group B's by 3.5 minutes. Group B users could only trigger static text/image pop-ups by scanning industrial equipment via WEB AR, with interactions limited to click-to-view and no dynamic feedback. Group C primarily followed guides for audio introductions, with only brief hands-on experiences at the intangible cultural heritage workshop, exhibiting the weakest overall interactivity. A 1.8-point gap was observed between Group A and Group B, whereas the difference between Group B and Group C was only 0.6 points, highlighting the marked enhancement in interactive engagement afforded by the XR-FRAME technology.

Across the experience dimensions covering immersion, usability, and enjoyment, another one-way ANOVA was carried out after verifying normality (all Shapiro-Wilk p -values > 0.05) and homogeneity of variances (Levene's test $p = 0.156 > 0.05$). The one-way ANOVA showed statistically significant differences at the 0.01 level ($F = 68.796$, $p = 0.000$), and subsequent Tukey's HSD post-hoc test revealed that both Group A (XR-FRAME) and Group B (WEB AR) achieved higher average scores than Group C (traditional narration), with Group A demonstrating a more prominent performance advantage relative to Group C. Based on actual experiences at the Beicang site, Group A users, through XR-FRAME's virtual-reality fusion reconstruction, could see holographic scenes of workers operating in the 1960s within existing textile factory buildings; combined with oral history audio, their immersion score (4.7/5) was considerably higher than that of Group C (2.3/5). Though Group B lacked dynamic holographic effects, WEB AR's 3D model overlay feature enabled 360° inspection of textile machinery details, yielding an experience score (3.8/5) that also outperformed Group C. Group C, relying solely on text panels and verbal narration, delivered monotonous information transmission with low levels of engagement and immersion, confirming that both technologies contribute to experience enhancement, with XR-FRAME delivering more pronounced improvements.

In the knowledge understanding dimension, which encompasses historical fact recall, industrial value recognition, and causal logic analysis, a third one-way ANOVA was performed after confirming normality (all Shapiro-Wilk p -values > 0.05) and

homogeneity of variances (Levene's test $p = 0.168 > 0.05$). The one-way ANOVA revealed extremely significant differences at the 0.01 level ($F = 28.459$, $p = 0.000$), and Tukey's HSD post-hoc test demonstrated that the pattern of average scores across groups was consistent with that observed in the experience dimension, with both technology-assisted groups outperforming the traditional guided tour group. Post-experiment assessments revealed that Group A users achieved 92% accuracy on knowledge points such as "the wartime logistics function of Beicang Textile Warehouse" and "the industrial purpose of wooden bracket structures in Soviet-style architecture," aligning with embodied cognition theory as XR-FRAME's "contextualized narrative" deeply integrates knowledge with immersive scenarios. Group B users, aided by WEB AR's "interactive timeline," achieved an 81% accuracy rate in sequencing key milestones of textile industry development higher than Group C's 56%. Group C users, receiving information passively, demonstrated only 48% accuracy in understanding deeper concepts like "the connection between textile technology and wartime logistics." Group A's knowledge comprehension score (89 points) was slightly higher than that of Group B (80 points), with both groups significantly outperforming Group C (52 points), confirming the auxiliary role of technology in knowledge acquisition, particularly XR-FRAME's ability to facilitate long-term memory formation through audio-visual coordination and interactive reinforcement.

Notably, the XR-FRAME framework introduced a gamified task mechanism that enabled users to actively explore industrial heritage historical details through task-driven means for example, simulating the assembly of machine tool parts to unlock subsequent historical explanations. This goal-oriented logic extended user stay time and allowed users to naturally grasp the industrial and technological characteristics of the Third Front Construction period, achieving dual goals of experiential fun and cultural understanding, while also verifying the key role of the feedback-evaluation-management cycle in optimizing user experience. Eye tracking data and questionnaire results further demonstrated XR-FRAME's advantages in promoting deep understanding of industrial heritage culture: Group A spent 78% of their gaze time on key information areas, which was substantially higher than the 52% observed in Group B and 35% in Group C. This focus stemmed from the system dynamically adjusting content presentation rhythm via attention heat maps, effectively stimulating exploration motivation - 87.6% of Group A participants reported that the AR experience sparked their interest in industrial technology history, compared to 64.3% in Group B and 41.2% in Group C. XR-FRAME's integration of technical presentation and humanistic narrative enhanced both cognitive understanding and emotional resonance, supported by built-in cognitive reinforcement strategies that facilitated the

transformation of short-term memory to long-term understanding.

Research results indicate that by integrating virtual information with real-world scenarios, this technology creates a highly immersive cultural experience, effectively addressing the one-way information transmission and lack of interactivity inherent in traditional guided tours. Users not only demonstrate a higher willingness to also experience significant improvements in knowledge acquisition, emotional resonance, and cultural identification. Compared to web-based AR and traditional tour guides, the mini-program based on the XR-FRAME framework offers structural advantages in terms of interactive depth, contextual restoration, and learning continuity. It demonstrates greater spatial adaptability and content capacity, particularly in complex industrial heritage environments. This achievement provides a replicable technical paradigm for the digital transformation of industrial heritage and empirically supports the innovation of cultural communication mechanisms within the context of cultural and tourism integration.

This study holds significant theoretical, methodological, and practical implications. Theoretically, it enriches the discourse on cultural heritage preservation and digital interpretation by integrating AR technology with constructivist and embodied cognition theories. From the perspective of constructivism, the XR-FRAME-based AR mini-program provides a scaffolded learning environment for visitors, allowing them to actively construct knowledge of industrial heritage through interactive behaviors (e.g., gesture control, gamified tasks) rather than passively receiving information. This aligns with constructivist core viewpoints that knowledge is actively constructed by individuals through contextual interaction rather than externally imparted. In contrast, Web AR merely enables basic click-to-view interactions with static text and images, failing to provide a supportive scaffolding for active knowledge construction, which explains why XR-FRAME outperforms Web AR in facilitating in-depth cognitive understanding. In terms of embodied cognition theory, the study verifies that AR technology's virtual-real fusion experience (e.g., holographic scene restoration, digital human interaction) enables visitors to form embodied perceptions of industrial heritage, as physical interactions and multi-sensory stimulation (audio-visual integration) link abstract historical knowledge to concrete sensory experiences, thereby deepening cognitive understanding and memory retention. Web AR, however, lacks dynamic virtual-real fusion and multi-sensory engagement, only offering superficial information presentation without triggering embodied perception, which further highlights XR-FRAME's advantage in activating visitors' multi-sensory participation and deepening their connection with industrial heritage. Methodologically, it offers a replicable framework for combining advanced technologies with cultural tourism, clarifying the specific implementation

details of the XR-FRAME framework to address the previous reproducibility dilemma. Practically, it enhances visitor engagement and understanding of industrial heritage sites, fostering greater appreciation and awareness, which contributes to advancing knowledge in this field and promoting innovative practices for cultural heritage revitalization.

Despite these contributions, this study has several notable limitations that require honest reflection and future addressing. First, the sample selection is biased: the 90 volunteers recruited primarily consist of young people (18-45 years old) from universities and online platforms, most of whom are proficient in digital technologies. This bias means the research findings may not be generalizable to older populations or individuals with low digital literacy, who may face barriers in using AR technology and thus exhibit different experience effects and knowledge acquisition outcomes. Second, the experiment adopts a short-term design (two-week duration), which may lead to novelty effects. Participants' high engagement and interest may stem from the novelty of AR technology rather than its long-term effectiveness in cultural heritage interpretation, and long-term retention of industrial heritage knowledge cannot be verified. Third, the study focuses on the technical and experiential effects of the XR-FRAME framework but neglects the influence of individual differences (e.g., prior knowledge of industrial heritage, cultural background) on the research outcomes, which may limit the depth and comprehensiveness of the findings. Additionally, the study does not explore the potential technical barriers (e.g., operation complexity of the AR mini-program) that may affect user experience, especially for non-technical groups.

Based on the above limitations and the research foundation of this study, specific future research directions are proposed to further promote the optimization and application of the XR-FRAME framework in industrial heritage revitalization. First, future research should adopt the AI-driven content generation module mentioned in the XR-FRAME framework to verify its adaptive narrative capability, generating personalized interpretation content based on visitors' individual characteristics (e.g., age, digital literacy, prior knowledge) to address the current one-size-fits-all content limitation. Second, expanding the sample scope to include older adults, individuals with low digital literacy, and visitors with different cultural backgrounds, comparing the experience effects and knowledge acquisition differences across groups to enhance the generalizability of the research findings. Third, extending the experimental duration to conduct long-term follow-up studies, tracking participants' long-term memory retention of industrial heritage knowledge and changes in interest, to eliminate the interference of novelty effects and verify the long-term effectiveness of the XR-FRAME-based AR mini-program. Fourth, delving deeper into intelligent and systematic upgrades of the framework: leveraging AI

for semantic-level content generation, employing large language models to dynamically produce personalized explanatory texts, and integrating computer vision to interpret tourist behavioral intentions, thereby enabling more adaptive and context-aware guided experiences. Fifth, addressing unresolved technical challenges: optimizing big data analytics for mining implicit user data (e.g., stay trajectories, interaction patterns) to refine cultural cognitive heat maps and spatial layouts; exploring the potential of 5G-A and edge computing in reducing latency for real-time 8K AR content delivery; and promoting long-term integration with city-level digital twin platforms, which requires interdisciplinary collaboration between computer science, cultural heritage research, and urban planning to realize its full potential.

Through technological synergy, theoretical deepening, and targeted solution of existing limitations, the XR-FRAME framework integrated with AR technology is poised to become a cornerstone for revitalizing industrial heritage, ensuring the sustainable transmission of cultural memory on a global scale.

List of abbreviations

ACAU	Activity-related authenticity
AI	Artificial intelligence
ANOVA	Analysis of variance
AR	Augmented reality
BIM	Building information modeling
EFA	Exploratory factor analysis
FEA	Finite element analysis
GIS	Geographic information system
HSD	Honestly significant difference
IPQ	Igroup Presence Questionnaire
IoT	Internet of things
Mask R-CNN	Mask region-based convolutional neural network
MR	Mixed reality
niVR	Non-immersive virtual reality
OBAU	Object-related authenticity
PRES	Sense of presence
RTK	Real-time kinematic
SAT	Satisfaction
SDK	Software development kit
SLAM	Simultaneous localization and mapping
SPSS	Statistical Package for the Social Sciences
SUS	System Usability Scale
SYSQ	System quality
VR	Virtual reality
XR	Extended reality
XR-FRAME	Extended reality, fusion, feedback, evaluation, and management

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Compliance with ethical standards

Ethical considerations

Ethical approval exemption was granted by the Ethics Committee of Suan Sunandha Rajabhat University (Certificate No. COE. 2-394/2025). All participants provided informed consent before participating in the study. Participants' confidentiality was maintained throughout the research, and the collected data were handled securely and used exclusively for research purposes. The study was conducted in accordance with the conditions specified in the ethics exemption certificate.

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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