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Can Location-Based Augmented Reality Support Cultural-Heritage Experience in Real-World Settings? Age-Related Engagement Patterns and a Field-Based Evaluation

Phichete Julrode [1], Darin Poollapalin [1], Sumalee Sangamuang [2], Kannikar Intawong [3] and Kitti Puritat [1,*]

[1] Department of Library and Information Science, Faculty of Humanities, Chiang Mai University, Chiang Mai 50200, Thailand; phichete.j@cmu.ac.th (P.J.); darin.poollapalin@gmail.com (D.P.)
[2] College of Arts, Media and Technology, Chiang Mai University, Chiang Mai 50200, Thailand; sumalee.sa@cmu.ac.th
[3] Faculty of Public Health, Chiang Mai University, Chiang Mai 50200, Thailand; kannikar.i@cmu.ac.th
* Correspondence: kitti.p@cmu.ac.th

Abstract

The Wua-Lai silvercraft community in Chiang Mai is experiencing a widening disconnect with younger visitors, raising concerns about the erosion of intangible cultural heritage. This study evaluates "Silver Craft Journey," a location-based augmented reality (LBAR) system designed to revitalize cultural engagement and enhance cultural-heritage experience through context-aware, gamified exploration. A quasi-experimental field study with 254 participants across three age groups examined the system's impact on cultural-heritage experience, knowledge acquisition, and real-world engagement. Results demonstrate substantial knowledge gains, with a mean increase of 7.74 points (SD = 4.37) and a large effect size (Cohen's d = 1.77), supporting the effectiveness of LBAR in supporting tangible and intangible heritage understanding. Behavioral log data reveal clear age-related engagement patterns: older participants (41–51) showed declining mission completion rates and reduced interaction times at later points of interest, which may reflect increased cognitive and physical demands during extended AR navigation under real-world conditions. These findings underscore the potential of location-based AR to enhance cultural-heritage experience in real-world settings while highlighting the importance of age-adaptive interaction and route-design strategies. The study contributes a replicable model for integrating digital tourism, embodied AR experience, and community-based heritage preservation.

Keywords: location-based augmented reality; cultural heritage learning; gamification; user engagement; digital heritage

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1. Introduction

The preservation of cultural heritage is undergoing a paradigm shift, moving beyond the conservation of tangible monuments to the safeguarding of Intangible Cultural Heritage (ICH)—the living expressions, skills, and community practices that define a culture's identity. According to the UNESCO Convention for the Safeguarding of the Intangible Cultural Heritage [1], preserving these dimensions requires active engagement rather than mere documentation. However, historic communities like Wua-Lai in Chiang Mai, Thailand, renowned for its Lanna silvercraft heritage, face a critical challenge. In recent years, the community has experienced a decline in tourist engagement, particularly among younger generations who prefer self-guided exploration over traditional tours. Consequently, the

deep cultural narratives and craftsmanship embedded in the silverwork tradition risk fading into obscurity, leading to both cultural detachment and reduced economic vitality for local artisans.

Digital technologies therefore need to provide more than visual enhancement; they must support participation, contextualized storytelling, and embodied learning [2,3]. Extended Reality (XR), particularly Location-Based Augmented Reality (LBAR), has emerged as a promising approach for connecting visitors with heritage in situ. By overlaying digital narratives onto the physical environment, LBAR allows users to construct knowledge through real-world movement and multisensory interaction. Empirical studies demonstrate that contextually grounded AR experiences can heighten curiosity, intrinsic motivation, and cognitive engagement [4,5]. Similarly, Location-Based Games (LBGs) have been shown to extend dwell time, reinforce cultural interpretation, and foster emotional connection with heritage environments [6,7]. Well-designed digital interactions can even translate cultural values—such as respect, empathy, and craftsmanship—into meaningful gameplay [8,9].

Despite the promise of LBAR, significant gaps remain in the literature. Prior studies have given limited attention to how such systems influence measurable learning outcomes regarding tangible versus intangible heritage. Furthermore, there is a scarcity of research examining how different age groups respond to AR-mediated cultural experiences in real-world settings. As heritage tourism encompasses diverse demographics, understanding how digital natives versus older adults process AR content is essential for designing inclusive and effective learning environments.

Addressing these gaps, this study evaluates "Silver Craft Journey," a gamified LBAR application developed to revitalize the Wua-Lai community. The system integrates GPS-based navigation, context-aware storytelling, and gamified micro-learning to connect visitors with the community's living heritage. Through a field evaluation, this study aims to: (1) empirically measure heritage knowledge gains facilitated by on-site AR, (2) analyze behavioral engagement patterns to identify interaction barriers, and (3) examine the moderating effect of age on learning and usability. The following research questions guide the inquiry:

RQ1: To what extent does the location-based AR application enhance cultural-heritage knowledge, and do participants across different age groups demonstrate comparable learning gains when interacting with real-world heritage locations?

RQ2: How do learning outcomes generated through the location-based AR experience differ among age groups, particularly in terms of cultural-heritage knowledge improvement?

RQ3: How do user engagement and perceived usability of the location-based AR system vary across age groups during their interaction with cultural-heritage points of interest?

RQ4: What design implications can be drawn for developing effective location-based AR applications that support cultural-heritage learning?

2. Related Works

2.1. Cultural Heritage and the Wua-Lai Community

The Wua Lai neighborhood, located south of Chiang Mai's old city walls, is a historic center of Lanna silver craftsmanship where silversmith lineages, Buddhist temples, and local marketplaces have shaped the community's cultural identity for generations (Figure 1). Historical and ethnographic studies document how techniques such as repoussé and chasing were transmitted through family workshops and temple networks, and how Tai Shan artisans who migrated in the nineteenth century embedded their craft knowledge within local rituals and social structures [10–12]. As a result, Wua Lai represents a living cultural landscape where tangible heritage—temples, tools, and artifacts—interacts closely with intangible heritage, including craftsmanship, oral traditions, and symbolic practices [12].

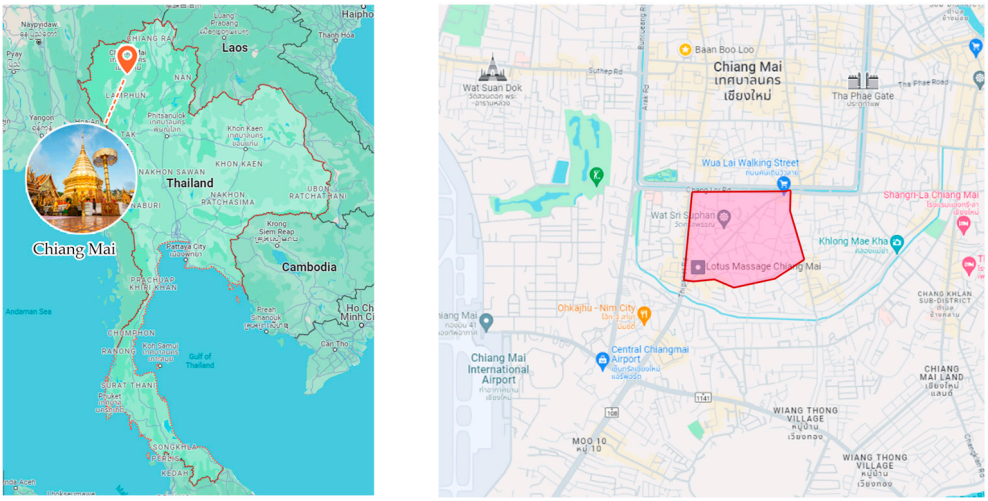


Figure 1. Geographic and local maps showing the location and cultural context of the Wua Lai community in Chiang Mai, Thailand.

In recent years, the community has faced declining visitor engagement, especially among younger travelers who rely on mobile technologies and prefer self-guided exploration, often resulting in superficial cultural interpretation [13]. Many tourists pass through Wua Lai without understanding its silvercraft heritage, weakening cultural connection and reducing economic opportunities for artisans. Studies on mobile heritage interpretation indicate that location-based AR can deepen exploration and meaning-making when aligned with visitor motivations [5]. Recent empirical work further shows that AR-supported storytelling enhances cultural appreciation, emotional immersion, and sense of place in heritage contexts [14], while immersive AR/VR systems can empower communities by supporting participatory narratives and reinforcing site-specific identity [15]. For Wua Lai, these findings underscore the need for digital tools that communicate craft traditions to digital-native audiences while maintaining cultural custodianship and sustaining local livelihoods.

2.2. Gamification for Learning and Engagement

Gamification—the use of game elements such as points, levels, rewards, and challenges in non-game contexts—has become a widely adopted strategy to enhance motivation and engagement in learning environments. Grounded in principles of self-determination, feedback loops, and goal-oriented interaction, gamification supports autonomy, competence, and relatedness among learners. A meta-analysis by Sailer and Homner (2020) showed small-to-moderate positive effects on motivation, cognitive learning, and behavior, particularly when social interaction and clear feedback are embedded [16]. Earlier reviews similarly positioned gamified learning as a growing field across educational settings, with evidence that effectiveness increases when game elements are tightly aligned with learning outcomes [17–20].

More recent studies emphasize the roles of context and personalization. Li, Ma and Shi (2023) reported consistent gains in cognitive engagement but variability in motivational effects depending on learner goals [21]. Oliveira et al. (2023) demonstrated that tailored gamification enhances persistence by adapting mechanics to learner profiles [22], while Peterson et al. (2023) identified a shift toward data-driven personalization and serious-game integration [23]. In cultural-heritage contexts, gamification that incorporates narrative coherence and emotional connection has been shown to deepen cultural understanding [24]. This trajectory extends to mobile heritage experiences, where AR-based serious games can promote inquiry, collaboration, and stronger engagement with cultural content [25]. Overall,

the literature indicates that gamification is most effective when grounded in pedagogical intent, contextual relevance, and meaningful feedback—principles that directly inform its application in location-based and heritage-focused mobile learning systems.

2.3. Augmented Reality for Cultural Heritage

Augmented Reality (AR) has become a central medium for cultural-heritage communication because it overlays digital information onto authentic places, enabling situated interpretation that merges observation with embodied action. Prior surveys show that AR and related immersive technologies support education, exhibition enhancement, exploration, reconstruction, and virtual museums when aligned with heritage goals and interaction constraints [2,26]. In museums and archeological contexts, AR scaffolds inquiry through spatially anchored 3D models, annotations, and narrative layers, promoting both cognitive understanding and affective engagement [27]. Field-based studies further indicate that AR improves attention and knowledge gains when tasks are clear and feedback is immediate, although benefits decline with high interface friction or weak content–place alignment [28].

Recent empirical work extends these insights to location-aware, community-connected deployments. Mission-driven AR exploration in a historic district in Greece, for example, enhanced heritage awareness and learning outcomes when mechanics, narrative, and routes were integrated with the local urban fabric [1]. Tourism research likewise shows that AR can increase visitor experience quality, satisfaction, and revisit intentions when used to complement curatorial interpretation [29]. A recent narrative synthesis highlights the importance of multidimensional evaluation frameworks incorporating usability, authenticity, emotional engagement, and cognitive load [30]. Additionally, AR-supported storytelling has been shown to elevate inspiration, cultural appreciation, and emotional immersion at heritage sites [14]. Collectively, these findings position AR as a culturally responsible medium capable of bridging tangible and intangible heritage through embodied, context-aware storytelling informed by rigorous, ethics-driven design.

2.4. Location-Based Games for Cultural Learning and Tourism

Location-Based Games (LBGs) blend digital interactivity with physical mobility, enabling players to engage with real-world environments through spatial missions, GPS-triggered events, and contextual storytelling. When virtual and physical layers are coherently integrated, LBGs have been shown to enhance motivation, situational awareness, and knowledge retention in cultural-heritage learning [6,7]. Historical-site-based games support navigation through heritage trails while prompting users to complete narrative-driven tasks, aligning with constructivist and situated-learning principles [31]. Empirical studies further demonstrate that carefully designed LBGs foster collaboration, curiosity, and cultural empathy, particularly when AR overlays and digital artifacts are used to reveal hidden layers of history [1,32].

Beyond educational settings, LBGs are increasingly applied in cultural tourism, where quest mechanics, collectibles, and rewards promote active participation and strengthen emotional attachment to heritage sites [33,34]. Recent work highlights how immersive AR storytelling can empower local communities by reinforcing cultural identity and improving communication within urban heritage contexts [15]. AR-supported inspiration models at World Heritage Sites also show positive effects on engagement, affective resonance, and revisit intention [14]. When designed with balanced gamification, coherent narratives, and respect for authenticity, LBGs operate as sustainable interfaces between learning and tourism, connecting visitors and communities through participatory digital storytelling.

3. Conceptual Framework

3.1. Conceptual Framework for Location-Based AR Heritage Learning

Figure 2 presents the conceptual framework guiding this study. The framework links system design components, cognitive–affective mechanisms, and cultural learning outcomes to explain how location-based AR supports heritage learning. The system design layer—comprising location-based AR game design and gamification elements—creates situated, interactive learning experiences that drive learner engagement [16]. These design features activate cognitive processes from the Cognitive Theory of Multimedia Learning, including attention, dual processing, and meaningful integration [35], alongside motivational processes grounded in Self-Determination Theory, such as autonomy, competence, and relatedness [36]. Together, these mechanisms facilitate heritage knowledge acquisition, which subsequently contributes to cultural empathy, appreciation, and intentions toward heritage preservation. The user's age group moderates these pathways by shaping how learners perceive, process, and respond to AR-based cultural experiences.

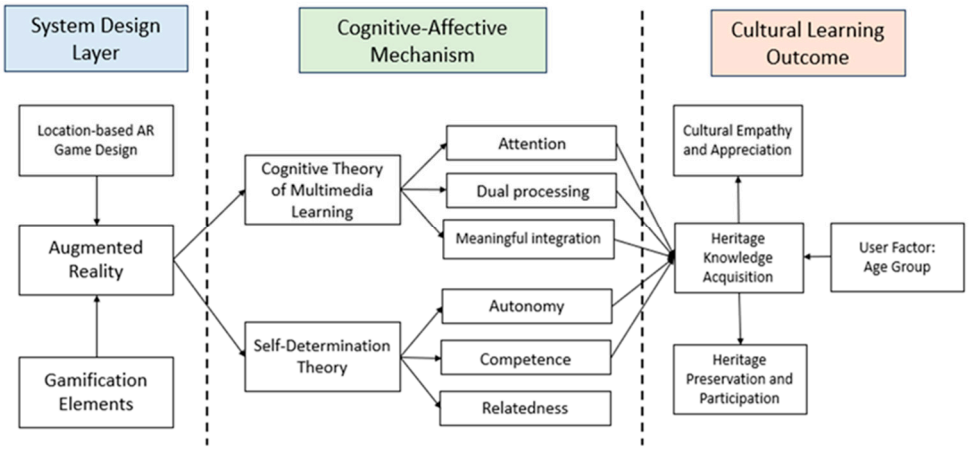


Figure 2. Presents the conceptual framework guiding this study.

3.2. Operational Definitions of Learning Outcomes

This study examines multiple learning-related constructs to represent different dimensions of cultural-heritage learning in a location-based augmented reality (AR) environment. These constructs span cognitive, affective, and experiential dimensions and are distinguished according to their roles in the conceptual framework (Figure 2). Table 1 summarizes the operational definitions, measurement roles, and theoretical grounding of each construct.

Table 1. Operational Definitions of Learning Outcomes and Related Constructs.

Construct	Operational Definition	Role in Conceptual Framework
Heritage Knowledge	Factual and conceptual understanding of Lanna silvercraft, including tools, processes, historical narratives, and symbolic meanings	Primary cognitive learning outcome
Tangible Heritage Learning	Understanding of physical artifacts and material craftsmanship encountered at heritage sites	Contextualized cognitive learning
Intangible Heritage Learning	Awareness of living traditions, cultural meanings, and community-based practices	Context-aware cultural learning
Cultural Awareness/Empathy	Affective appreciation and reflective understanding of cultural values beyond factual recall	Affective learning outcome
User Engagement	Experiential construct capturing focused attention, usability, aesthetic appeal, and reward during AR interaction	Facilitating experiential condition

4. System and Game Design

4.1. System Overview and User Interface

The Silver Craft Journey was developed as a location-based augmented reality (AR) learning system that integrates mobility, spatial interaction, and gamified cultural engagement. Drawing on the exploratory concept of Pokémon GO [37], the system guides players through the Wua Lai community using GPS-based navigation, enabling them to physically tour real heritage locations while simultaneously learning about Lanna silvercraft traditions embedded in those spaces. As illustrated in Figure 3, the user interface supports smooth progression through login, map-based navigation, AR scanning, and quiz interaction. Each heritage location operates as a digital checkpoint where players encounter AR content, complete cultural tasks, and accumulate cultural knowledge points. The system is structured around three core design layers: (1) exploratory navigation that encourages users to move through authentic cultural environments; (2) cultural learning tasks that connect AR interaction with site-specific silvercraft knowledge; and (3) motivational gamification elements that enhance cultural-heritage engagement [38], including badges, points, and progress tracking. This integrated approach transforms physical heritage environments into interactive learning experiences, allowing users to engage in on-site cultural exploration while reinforcing intrinsic motivation and spatial memory.

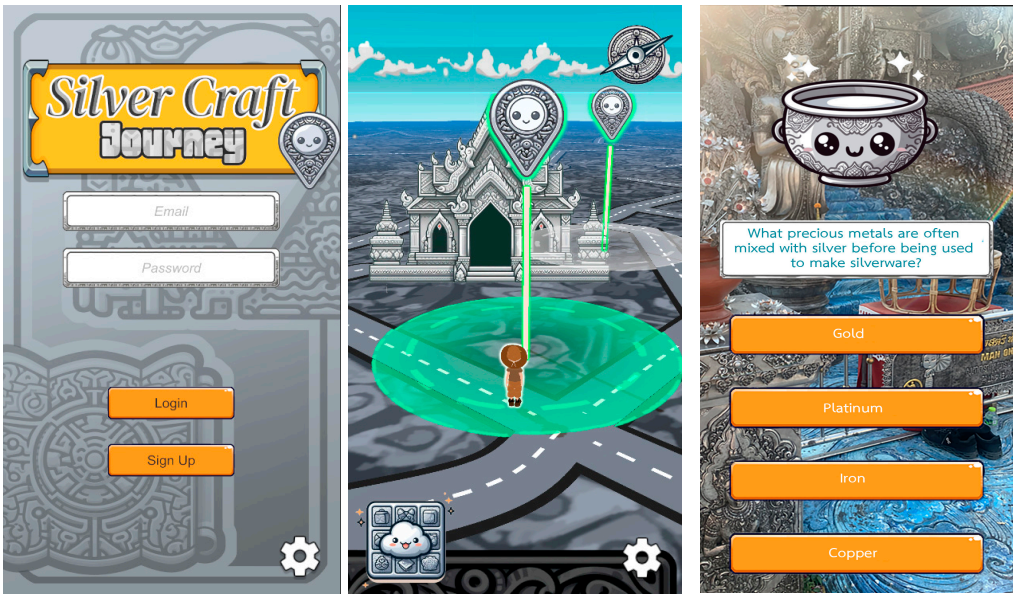


Figure 3. The user interface of the Silver Craft Journey application, illustrating the login screen, AR navigation map, and quiz interaction.

From a technical perspective, the system was implemented as a mobile, location-based AR application running on both Android and iOS smartphones, using GPS-based positioning for outdoor navigation and camera-based AR tracking for on-site interaction. GPS accuracy varied across devices and operating systems; in field use, lower-end or older Android devices occasionally showed reduced positional accuracy, whereas iOS devices generally provided more stable readings under similar conditions. Tracking robustness was influenced by lighting, partial occlusion, camera performance, and user movement. Overall, on-site observation indicated no critical issues affecting AR usability or task completion, reflecting the maturity of contemporary smartphone technologies for practical real-world AR deployment, although performance may vary depending on device specifications and network conditions.

4.2. Points of Interest and Cultural Learning Design

The game world is anchored by six Points of Interest (POIs), selected to represent both tangible and intangible dimensions of Lanna cultural heritage and aligned with the classifications shown in Figures 4–6 and Table 2, while their spatial arrangement within the Wua Lai community is illustrated in Figure 7. The intangible cultural layer includes (1) the Lanna Traditional Thai Art Study Center, which emphasizes knowledge transmission through artisan-led workshops, and (2) Wua Lai Walking Street, a dynamic cultural market featuring live craftsmanship and local performances. The tangible heritage layer consists of (3) the Wat Muen San Silverware Museum, which exhibits traditional Thai metalwork; (4) the Wat Sri Suphan Pagoda, a sacred site demonstrating historical Buddhist artistry; (5) the Wat Sri Suphan (Silver Temple), globally recognized as the first silver temple; and (6) the Wat Muen San Temple, honored as the second silver temple in the world. Together, these POIs form the narrative backbone of the journey, structuring the player's movement and framing the cultural content encountered at each point. The sequential movement between POIs encourages continuous learning, reflection, and cultural immersion.



Figure 4. Intangible heritage POIs: Lanna Art Study Center and Wua Lai Walking Street.

Table 2. Point of Interest (POI) in the Silver Craft Journey Application.

Category	Area of Interest	Description of Location
Intangible Knowledge	Lanna Traditional Thai Art Study Center	A center dedicated to preserving and teaching Lanna arts. It showcases traditional artworks, offers workshops, and provides educational programs for visitors seeking cultural immersion.
	Wua Lai Walking Street	A vibrant street famous for its weekly market of local crafts and Thai cuisine. It serves as a cultural hotspot where visitors experience performances and traditional market life.
Tangible Knowledge	Wat Muen San Silverware Museum	Located in the historic Wat Muen San, this museum highlights the artistry of traditional Thai silverware and offers insight into Lanna metalwork heritage.
	Wat Sri Suphan Pagoda	A 500-year-old pagoda symbolizing Buddhist art and architecture. It serves as a sacred relic site and a focal point for meditation and craftsmanship.
	Wat Sri Suphan (The First Silver Temple)	Known as the world's first silver temple, it features intricate silver decorations that exemplify traditional Lanna craftsmanship.
	Wat Muen San (The Second Silver Temple)	The world's second silver temple, celebrated for its elaborate silverwork and reflection of Wua Lai's heritage.



Figure 5. Tangible heritage POIs: Silverware Museum and the two Silver Temples.



Figure 6. Tangible heritage Points of Interest: Wat Sri Suphan, the first silver temple, and Wat Muen San, the second silver temple.



Figure 7. Map of the Wua Lai community showing the locations of the six cultural Points of POIs.

4.3. Monster Design and AR Gameplay Mechanism

Complementing the spatial learning structure is the AR monster design system, which transforms authentic Wua Lai silvercraft objects into collectible digital characters. As shown in Figure 8, fifteen monsters were designed based on real silver artifacts such as ceremonial bowls, betel containers, lidded jars, incense burners, and traditional silver accessories. Each monster retains key visual features—silhouette, motifs, and craftsmanship details—while being stylized to enhance approachability and emotional engagement. During gameplay, players must capture at least one monster at each POI before progressing to the next location. When an AR monster appears, the system triggers a heritage-themed quiz related to silvercraft processes, materials, symbolic meaning, or historical narratives. Correct responses lead to successful capture and point accumulation, while uncaptured monsters remain silhouetted in the collection interface. This mechanism combines spatial exploration, micro-learning, and reward feedback, reinforcing cultural understanding through repeated interaction, recognition, and narrative-based play.



Figure 8. Cultural-heritage-inspired monster designs derived from traditional Lanna silvercraft artifacts and integrated into the gameplay system.

4.4. User Experience Flow and Gameplay Procedure

From the user's perspective, interaction with the Silver Craft Journey follows a structured procedural flow before, during, and after the site visit. Before the visit, users launch the mobile application on-site, review a brief introduction explaining the purpose of the experience, and receive basic instructions on navigation and AR interaction. During the visit, users follow a GPS-based map to sequential Points of Interest (POIs), where they scan the environment to trigger AR content, complete short cultural tasks or quizzes, and collect in-game rewards. Progression between POIs is unlocked sequentially to guide users along the intended heritage route, while visual cues on the map indicate the next destination. After completing the visit, users review their progress and accumulated achievements within the application. Throughout gameplay, lightweight guidance—such as on-screen prompts, task instructions, and navigation indicators—is provided to support user orientation without interrupting exploration.

5. Methodology

5.1. Research Design

This study employed a quantitative quasi-experimental design integrating pre- and post-test assessments with gameplay analytics and post-experience questionnaires. The

research aimed to examine how interaction with the Silver Craft Journey application enhanced cultural knowledge, engagement, and motivation among visitors at Wat Sri Suphan. The pre- and post-tests measured changes in participants' heritage knowledge and cultural empathy, while gameplay data automatically recorded in-app behavior such as time on task, number of locations visited, and mission completion rates. In addition, a structured questionnaire evaluated participants' perceptions of usability, engagement, and learning satisfaction after gameplay. The combination of performance metrics and self-reported data provided a comprehensive understanding of the learning impact and user experience.

5.2. Participants

Participants were recruited from local visitors and tourists at Wat Sri Suphan, a cultural landmark within the Wua Lai community in Chiang Mai, Thailand. A total of 254 participants (aged 20–51 years) voluntarily took part in testing the Silver Craft Journey prototype. Among them, 105 were male and 149 were female. Most participants were casual visitors interested in exploring the temple and its silvercraft heritage, with varying levels of familiarity with mobile or AR-based applications. Prior to gameplay, all participants received a digital briefing outlining the research objectives, procedures, and data-privacy policy. Participation was entirely voluntary, and each participant provided digital informed consent through the system interface before beginning the activity. The demographic characteristics of the participants are presented in Table 3. As a token of appreciation, participants received a small commemorative souvenir after completing the test session.

Table 3. Demographic Profile of Participants (N = 254).

Characteristic	Category	Frequency (N)	Percentage (%)
Gender	Male	105	41.3
	Female	149	58.7
Age Group (years)	20–30	92	36.2
	31–40	94	37.0
	41–51	68	26.8
Visitor Type	Local Visitors (Chiang Mai residents)	132	52.0
	Domestic Tourists (from other provinces)	98	38.6
	International Tourists	24	9.4
Experience with Mobile Applications	Basic (daily use, non-AR)	180	70.9
	Moderate (occasional AR/game users)	61	24.0
	Advanced (frequent AR/game users)	13	5.1

5.3. Instruments

5.3.1. Heritage Knowledge Questionnaire

The Heritage Knowledge Questionnaire was developed to assess participants' acquisition of cultural and historical knowledge related to the Wua-Lai silvercraft tradition before and after interacting with the Silver Craft Journey application. The instrument comprised 30 multiple-choice items covering both tangible and intangible heritage domains, including silver-making tools, craftsmanship processes, ritual symbolism, traditional narratives, and locally embedded beliefs. Each correct response received one point, yielding a total possible score of 30. Content validity was established through expert review using the Index of Item–Objective Congruence (IOC), with three specialists in digital heritage and instructional design providing an average IOC score of 0.67, indicating acceptable alignment between item content and learning objectives. Prior to field implementation, the questionnaire underwent pilot testing to ensure clarity and suitability for visitors. Internal consistency reliability was subsequently evaluated using Cronbach's alpha based on data from the main study, resulting in $\alpha = 0.78$, which reflects satisfactory reliability for measuring her-

itage knowledge in this cultural-heritage AR context. The instrument was administered twice—once as a pre-test and again immediately after gameplay—to determine learning gains attributable to the location-based AR experience.

5.3.2. User Engagement Scale Questionnaire

The User Engagement Scale (UES) was administered after gameplay to evaluate participants' engagement and affective involvement during the AR experience. The instrument comprised 12 items derived from the established User Engagement Scale proposed by O'Brien et al. [39], measuring four dimensions: Focused Attention, Perceived Usability (reverse-scored), Aesthetic Appeal, and Reward. The original construct structure of the UES was retained, with only minor wording adaptations made to reflect the location-based AR cultural-heritage context; no new items or dimensions were introduced. Each item employed a 5-point Likert scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree). The use of this validated multidimensional scale allows engagement dimensions relevant to interactive and immersive AR experiences to be captured in a manner consistent with prior HCI research. Responses from this questionnaire were further triangulated with gameplay analytics to interpret participants' engagement and their contributions to heritage preservation and participatory behaviors, as shown in Appendix A Table A1.

5.3.3. Game Log Data

Gameplay log data were automatically recorded on the project server, capturing users' navigation behavior through GPS-based tracking. The system logged total play time and the sequence in which participants reached each Point of Interest (POI), allowing the platform to verify whether players followed the intended heritage route. These GPS-derived behavioral traces provided objective indicators of participation within the location-based AR environment and complemented the self-reported engagement results from the UES questionnaire.

5.4. Research Procedure

The research procedure was conducted as a field-based experiment over one week at Wat Sri Suphan in the Wua Lai community, Chiang Mai, as illustrated in Figure 9. A total of 351 participants were initially screened on-site; however, 67 individuals who did not provide online consent, complete the pre-test, or engage in gameplay for at least 15 min were excluded, resulting in a final sample of 254 participants. All eligible participants first completed a pre-test assessing heritage knowledge and were subsequently categorized into three age groups: 20–30 years (N = 92), 31–40 years (N = 94), and 41–51 years (N = 68).

Each participant then engaged in a single gameplay session using the Silver Craft Journey application for no longer than 120 min, during which they explored multiple POIs representing both tangible and intangible aspects of Lanna silvercraft culture. The system automatically recorded gameplay metrics, including navigation paths, time on task, and mission completion data. After completing gameplay, participants completed post-test measures evaluating heritage knowledge, user engagement, and in-app learning performance. All participants provided digital informed consent, and the entire data collection process was completed within one week under consistent on-site environmental conditions to ensure reliability and comparability across sessions. The study was conducted in accordance with the Declaration of Helsinki and approved by the Chiang Mai University Research Ethics Committee (COA No. 041/67), with all collected location and gameplay data anonymized prior to analysis.

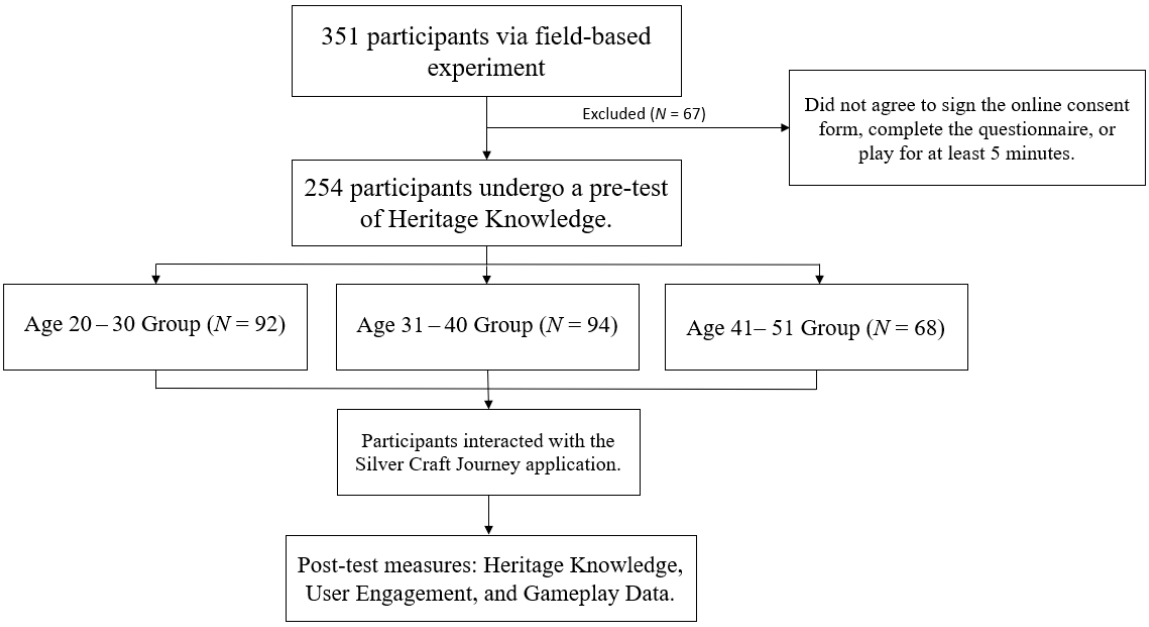


Figure 9. Research procedure and participant flow diagram.

5.5. Data Collection and Analysis

Data were collected from three primary sources: pre- and post-test scores of the Heritage Knowledge Questionnaire, in-app gameplay logs, and post-experience questionnaires assessing engagement and motivation. All data were obtained on-site during the one-week field experiment at Wat Sri Suphan. Descriptive statistics, including mean and standard deviation, were used to summarize participant characteristics and overall performance. A paired-sample *t*-test was employed to examine differences between pre- and post-test scores, determining learning gains attributable to interaction with the Silver Craft Journey application. For these within-subject comparisons, effect sizes (Cohen's d) were calculated for paired samples using the mean of the pre–post difference scores divided by the standard deviation of the differences. In addition, correlation analysis was conducted to explore relationships among gameplay behavior, engagement, motivation, and learning outcomes. Group comparisons by age were further analyzed using one-way ANOVA to identify potential differences in learning and engagement across demographic segments. All statistical analyses were performed using a significance level of $p < 0.05$.

6. Results

6.1. Result of Heritage Knowledge

A paired-sample *t*-test was conducted to evaluate changes in heritage knowledge across age groups, and the results are summarized in Table 4. Overall, participants demonstrated a significant improvement from the pre-test (M = 8.11, SD = 3.16) to the post-test (M = 15.85, SD = 3.10), yielding a substantial mean learning gain of 7.74 points (SD = 4.37), t = 28.27, $p < 0.001$, with a large effect size (Cohen's d = 1.77). When examined by age group, all groups showed statistically significant increases: the 20–30 group improved by 8.34 points (SD = 4.38), t = 18.27, $p < 0.001$, d = 1.91; the 31–40 group demonstrated the highest effect size with a gain of 8.24 points (SD = 3.91), t = 20.41, $p < 0.001$, d = 2.11; and the 41–51 group improved by 6.26 points (SD = 4.66), t = 11.09, $p < 0.001$, d = 1.35.

A one-way ANOVA was conducted to examine differences in learning gain across the three age groups, and the results (Table 5) revealed a statistically significant effect of age on learning outcomes, F(2, 251) = 5.54, $p = 0.004$. To further identify which groups differed, a Tukey HSD post hoc analysis was performed (Table 6). The results showed

no significant difference between the 20–30 and 31–40 groups (mean difference = 0.10, p = 0.912), indicating comparable improvement levels. However, both the 20–30 and 31–40 groups demonstrated significantly higher learning gains than the 41–51 group, with mean differences of 2.08 (p = 0.006) and 1.98 (p = 0.009), respectively.

Table 4. Result of A paired sample *t*-test of Heritage Knowledge between Group.

Group	N	Pre-Test Mean (SD)	Post-Test Mean (SD)	Learning Gain Mean (SD)	t	*p*-Value	Cohen's d
20–30	92	8.74 (2.82)	17.08 (2.91)	8.34 (4.38)	18.27	<0.001	1.91
31–40	94	8.03 (3.20)	16.27 (2.30)	8.24 (3.91)	20.41	<0.001	2.11
41–51	68	7.37 (3.42)	13.63 (3.17)	6.26 (4.66)	11.09	<0.001	1.35
All	254	8.11 (3.16)	15.85 (3.10)	7.74 (4.37)	28.27	<0.001	1.77

Table 5. One-way ANOVA of Learning Gain Across Age Groups.

Source	SS	df	MS	F	*p*-Value
Between Groups	203.73	2	101.86	5.54	0.004
Within Groups	4618.64	251	18.40	-	-
Totals	4822.36	253	-	-	-

Table 6. Multiple Comparative Analyses of Learning Gain Across Age Groups (Tukey HSD).

(I) Group	(J) Group	Mean Difference (I–J)	Std. Error	Sig.
20–30	31–40	0.11	0.33	0.912
20–30	41–51	2.08	0.74	0.006
31–40	41–51	1.98	0.75	0.009

6.2. Result of User Engagement Scale

Descriptive statistics of the UES across age groups are presented in Table 7. Overall, participants reported moderately high engagement, with the total UES mean score of 3.99 (SD = 0.44). The 20–30 age group showed the highest overall engagement (M = 4.15, SD = 0.42), followed by the 31–40 group (M = 4.02, SD = 0.45), while the 41–51 group reported lower engagement levels (M = 3.73, SD = 0.47). Across the UES subdimensions—Focused Attention, Perceived Usability, Aesthetic Appeal, and Reward—a similar pattern was observed. Younger participants (20–30) consistently reported the highest scores, particularly in Focused Attention (M = 4.25, SD = 0.44) and Aesthetic Appeal (M = 4.30, SD = 0.45), whereas the oldest group (41–51) scored the lowest across all dimensions.

Table 7. Descriptive statistics of UES across age groups.

Group	N	Focused Attention Mean (SD)	Perceived Usability Mean (SD)	Aesthetic Appeal Mean (SD)	Reward Mean (SD)	UES Total Mean (SD)
20–30	92	4.25 (0.44)	3.95 (0.48)	4.30 (0.45)	4.00 (0.44)	4.15 (0.42)
31–40	94	3.95 (0.47)	3.90 (0.50)	4.22 (0.47)	3.98 (0.46)	4.02 (0.45)
41–51	68	3.45 (0.50)	3.88 (0.53)	3.65 (0.52)	3.96 (0.48)	3.73 (0.47)
All participants	254	3.94 (0.48)	3.91 (0.50)	4.06 (0.50)	3.98 (0.47)	3.99 (0.44)

A one-way ANOVA was conducted to examine whether user engagement (UES) differed across age groups, and the results are presented in Table 8. The analysis revealed a statistically significant difference in UES scores among the three groups, F(2, 251) = 17.8, $p < 0.001$, indicating that age had a meaningful effect on engagement levels. Post hoc pairwise comparisons using the Tukey HSD test (Table 9) showed that both the 20–30 and 31–40 groups reported significantly higher engagement than the 41–51 group, with mean differences of 0.42 ($p < 0.001$) and 0.29 ($p < 0.001$), respectively. However, the difference

between the 20–30 and 31–40 groups did not reach statistical significance (p = 0.067), suggesting comparable engagement levels among younger and middle-aged participants.

Table 8. One-way ANOVA of UES Across Age Groups.

Source	SS	df	MS	F	*p*-Value
Between Groups	7.04	2	3.52	17.8	<0.001
Within Groups	49.69	251	0.20	-	-
Totals	56.73	253	-	-	-

Table 9. Multiple Comparative Analyses of UES Across Age Groups (Tukey HSD).

(I) Group	(J) Group	Mean Difference (I–J)	St. Error	Sig.
20–30	31–40	0.13	0.065	0.067
20–30	41–51	0.42	0.071	<0.001
31–40	41–51	0.29	0.071	<0.001

6.3. Result of Game Log Data

Analysis of the game log data revealed clear differences in task completion performance across age groups, as illustrated in Figure 10. Participants aged 20–30 consistently achieved the highest completion rates across all six locations, ranging from 89% to 100%. The 31–40 group showed a similar pattern, with slightly lower completion rates than the youngest group but still maintaining high performance levels across locations. In contrast, the 41–51 group exhibited a pronounced decline in completion rates, particularly from Location 3 onward, where the rate decreased to 85%, 61%, 55%, and eventually 47% at the final location.

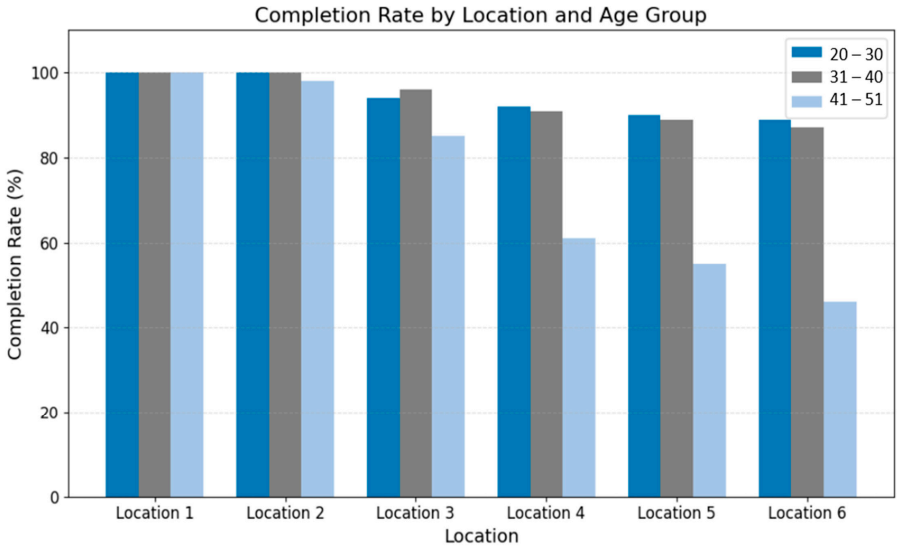


Figure 10. The completion rates at each game location across the three age groups.

In addition to completion rates, the time spent at each location was analyzed as a descriptive behavioral indicator to further examine differences across age groups, as illustrated in Figure 11. The 20–30 and 31–40 groups showed relatively consistent time-use patterns across all locations, spending approximately 9–11 min per task, reflecting stable interaction durations across tasks rather than direct measures of engagement or performance. In contrast, the 41–51 group displayed a marked reduction in time spent from Location 3 onward, decreasing from 6.4 min at Location 3 to 4.9, 4.1, and finally 3.4 min at Location 6, which may reflect a range of factors such as task efficiency, fatigue, navigation difficulty, or selective disengagement rather than a single underlying cause.

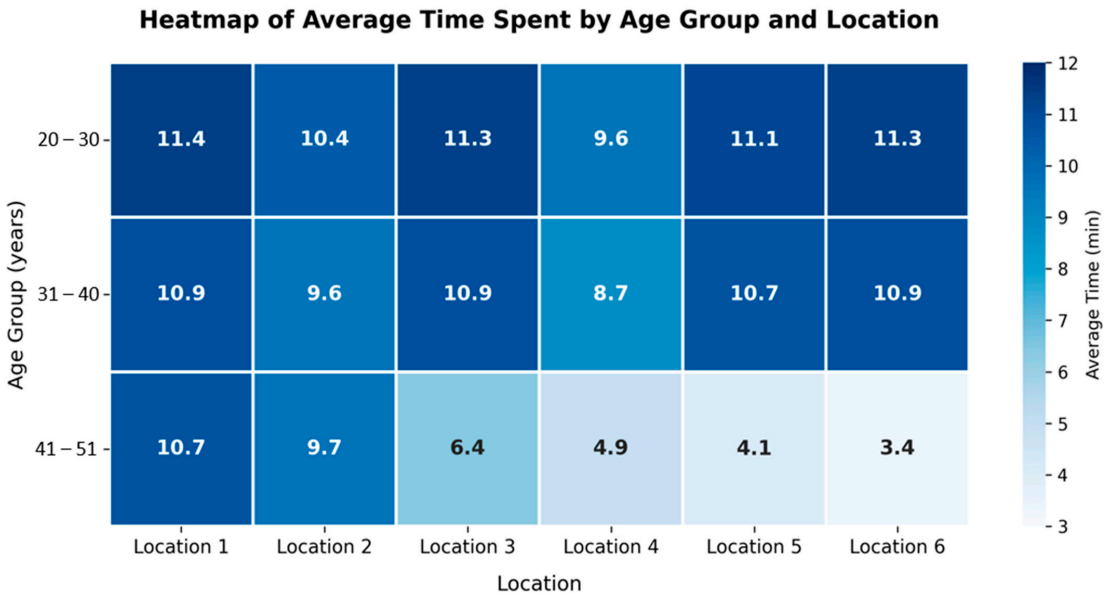


Figure 11. Heatmap of average time spent at each location by age group.

Figure 12 further illustrates age-related differences in gameplay progression using the average number of monsters collected at each location as a descriptive indicator. Participants in the 20–30 and 31–40 age groups showed relatively stable monster-collection patterns across all six locations, with the younger group consistently collecting slightly more monsters per location. By contrast, the 41–51 age group exhibited a gradual decline in monster collection from Location 3 onward, corresponding to the reduction in time spent observed in Figure 11. These patterns indicate that age-related differences in in-game progression may reflect a combination of interaction duration, navigation demands, and sustained participation across locations, rather than time-based efficiency or learning performance alone. Considered together with Figures 10 and 11, Figure 12 provides complementary evidence of how behavioral patterns in real-world AR use vary across age groups.

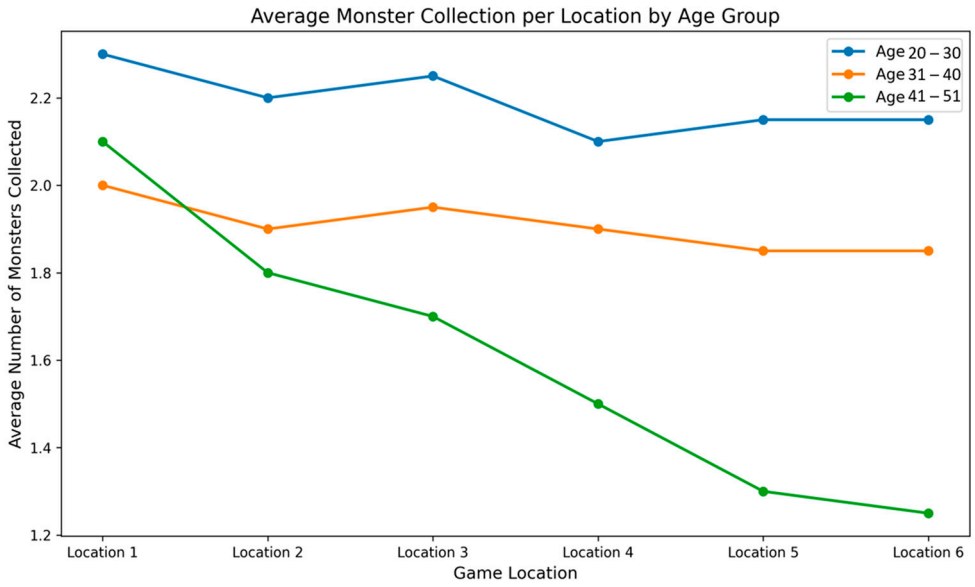


Figure 12. Average number of monsters collected per location across age groups.

7. Discussion

7.1. Effects of Cultural Heritage Learning

Regarding the effectiveness of the location-based AR application in enhancing cultural-heritage knowledge (RQ1), the findings indicate that the Silver Craft Journey was associated with clear improvements across all age groups. Participants demonstrated substantial pre–post gains, suggesting that context-aware AR can support the learning of both tangible and intangible heritage content. The integration of spatial navigation, cultural storytelling, and interactive quizzes appears to have enabled participants to construct knowledge meaningfully during real-world exploration. When comparing outcomes across age groups (RQ2), younger and middle-aged participants achieved higher gains than older adults, which may be partly attributable to greater familiarity with mobile interaction, AR interfaces, and game-based tasks, potentially facilitating smoother engagement and more efficient cognitive processing. Overall, the embodied, place-based learning environment may have allowed users to anchor cultural information to physical locations, reinforcing memory and comprehension. The relatively lower gains among the 41–51 age group may reflect slower interaction speed, lower digital fluency, and the increased physical or cognitive effort required during on-site navigation [40], although these differences should be interpreted cautiously. Some of these differences may also have been influenced by technical frictions—such as intermittent GPS drift or AR tracking instability—that could have added unintended cognitive load rather than reflecting true variation in learning performance. These combined factors may have reduced the resources available for processing new cultural information.

These outcomes are consistent with recent research demonstrating that AR enhances understanding when learning is closely tied to authentic physical contexts. Location-based AR applications for historic districts have reported significant increases in knowledge and cultural awareness among diverse visitor groups [1]. Reviews of AR for cultural heritage suggest that situated AR narratives improve comprehension, emotional engagement, and meaning-making [2,26]. Recent syntheses further emphasize that AR effectiveness depends on narrative coherence, context alignment, and evaluation rigor, particularly in cultural settings [30]. Studies of mobile AR learning also highlight that spatially anchored tasks improve attention and knowledge retention through embodied interaction [41]. Likewise, emerging work on location-based AR for heritage tourism indicates that AR-supported wayfinding and contextual storytelling strengthen visitor learning and meaning-making during real-site exploration [14]. Together, these findings suggest that well-designed, location-based AR environments such as the Silver Craft Journey can enhance cultural-heritage learning while underscoring the need for usability and demographic sensitivity in system design.

7.2. Behavioral Engagement Patterns in Real-World AR Use

Analysis of behavioral engagement (RQ3) shows that participants interacted actively with the location-based AR system, demonstrating consistent movement across POIs, steady completion of AR-triggered missions, and meaningful participation in quiz tasks. Younger and middle-aged groups recorded longer play durations and higher POI completion rates, which may reflect smoother navigation and greater confidence with mobile interaction. In contrast, the oldest group in this study (41–51) tended to progress more slowly, with shorter active engagement intervals and fewer optional interactions, suggesting that physical navigation demands and interface complexity may have contributed to reduced behavioral intensity. Nevertheless, all groups engaged sufficiently with the AR content to complete the core storyline, indicating that the system maintained essential usability in a real-world cultural environment.

These engagement patterns align with prior research demonstrating that age, digital proficiency, and physical mobility shape user experience in outdoor AR applications. Studies of mobile AR usage consistently report that younger adults exhibit more fluid interaction behavior, faster task completion, and greater exploratory movement [39]. Systematic evaluations of AR in heritage tourism likewise suggest that interface familiarity strongly influences engagement depth, particularly during location-based navigation and map-based decision-making. Recent field studies also indicate that embodied AR tasks—such as scanning markers, walking between POIs, and completing in situ challenges—tend to produce higher engagement among digitally fluent users while introducing additional cognitive load for older participants [14]. Consistent with these findings, the behavioral data in this study indicate that real-world AR engagement is shaped by a combination of mobility demands, digital fluency, and demographic factors, underscoring the importance of age-aware interaction design for cultural-heritage AR systems.

7.3. Design Implications for AR-Based Cultural Heritage Systems

The findings of this study yield several design implications for developing effective AR-based cultural-heritage systems (RQ4). First, the overall learning gains and engagement trends suggest that cultural content should be embedded directly within real heritage sites through spatial cues, contextual storytelling, and short interactive quizzes. Second, the behavioral data indicate that user engagement begins to decline noticeably at the fourth POI, particularly among the oldest group in the sample. This suggests that the optimal duration for a complete location-based AR experience should be kept within 30–40 min, allowing users across age groups to complete the activity without excessive physical or cognitive fatigue. Third, the game structure—especially the collection of silvercraft-inspired monsters—demonstrated that gamification is an essential component for cultural-heritage AR, introducing variety and creating multiple motivational pathways. Collection-based mechanics enhanced replayability and experiential diversity for users who enjoy completing sets or engaging with game-like challenges, indicating that gamification elements can be strategically aligned with diverse motivational profiles. Fourth, the involvement of local stakeholders—including community leaders, artisans, and small businesses—can enrich visitor experience by providing real-time guidance, cultural context, and personalized recommendations, thereby strengthening both authenticity and community engagement.

Beyond these practical considerations, the findings also offer important theoretical implications for AR-mediated cultural-heritage learning. The observed age-related differences in learning performance and behavioral engagement contribute to a more nuanced understanding of embodied and location-based learning theory, suggesting that cognitive load, spatial pacing, and digital fluency operate as moderating mechanisms in real-world AR environments. The decline in engagement after the fourth POI provides empirical support for the idea that AR-based micro-learning must be temporally bounded, thereby refining gamification theory by highlighting an optimal engagement window in outdoor, movement-intensive experiences. Moreover, the integration of spatial navigation, contextual storytelling, and collectible artifacts points toward an emergent set of design principles—age-adaptive task structuring, cognitive-load alignment, and motivationally balanced gamification—that can inform future theoretical models of culturally grounded AR design.

These implications are consistent with broader findings in AR and heritage research. Prior studies highlight that narrative coherence, cultural authenticity, and low interaction friction are critical for sustaining visitor engagement in outdoor AR experiences [2,30]. Research in AR tourism similarly emphasizes the importance of adaptive navigation and appropriately scoped route design to improve usability for older or less digitally

experienced participants [14]. Additionally, mobile AR learning studies suggest that modular tasks and tailored reward systems can accommodate differences in digital fluency and intrinsic motivation. Taken together, these insights support a design framework that emphasizes contextualized learning, age-aware task structuring, and motivationally responsive gamification—while also extending existing theories of embodied learning and AR-based cultural engagement.

7.4. Limitations and Future Research Directions

Although the Silver Craft Journey demonstrates clear benefits for cultural-heritage learning across age groups, several limitations should be acknowledged. The field deployment was limited to a single week, constraining the observation of seasonal visitor patterns and long-term knowledge retention. Learning outcomes were assessed immediately after the intervention, capturing short-term gains but not sustained learning effects. In addition, the use of identical heritage knowledge questionnaires for pre- and post-testing may introduce test–retest effects related to item familiarity rather than genuine knowledge acquisition; this design was adopted to enable within-participant comparison under field conditions and should be considered when interpreting the results.

The system's availability in only two languages may restrict access for international audiences, and the evaluation focused primarily on cognitive outcomes and self-reported engagement, without assessing broader cultural or tourism-related impacts. While gameplay analytics provided behavioral insights, the absence of qualitative inquiry limited deeper understanding of users' meaning-making processes. Moreover, technical factors inherent to outdoor AR—such as lighting variability, GPS drift, device performance, and the physical demands of navigation—along with visual fatigue and device ergonomics, may have affected older participants' engagement. Finally, the single-group quasi-experimental design limits causal comparison with alternative heritage-interpretation approaches, and the strong cultural and spatial specificity of the Wua-Lai community constrains the direct generalizability of the findings.

Future research should address these limitations by leveraging generative AI to create adaptive, context-aware POIs and personalized storytelling pathways that respond to users' progress, preferences, and real-time environmental conditions. Large language models may also support multilingual accessibility and reduce reliance on manually authored cultural content. Longitudinal studies are needed to determine whether AR-mediated heritage experiences foster sustained cultural appreciation, behavioral change, or measurable socio-economic benefits for local communities. Mixed-methods approaches that combine behavioral analytics, physiological or cognitive-load indicators, and qualitative inquiry would provide a more holistic understanding of user experience across demographic groups. Future studies should incorporate controlled comparative designs (e.g., AR-based experiences versus guided tours or self-guided visits) to enable stronger causal inference. Finally, expanding evaluation frameworks to account for accessibility, mobility constraints, sensor reliability, and inclusive interaction design will be essential for developing AR systems that equitably support both younger digital-native users and older visitors. Advancing these research directions will contribute to the development of more adaptive, scalable, and culturally responsive AR platforms for real-world heritage learning.

8. Conclusions

This study demonstrates that a location-based AR system can meaningfully enhance cultural-heritage learning by integrating spatial navigation, contextual storytelling, and gamified micro-learning within an authentic community environment. Participants across all age groups achieved significant knowledge gains, and behavioral log data confirmed

sustained engagement, although older adults showed lower completion rates and shorter interaction durations, indicating the moderating influence of age on AR usability. These findings highlight that culturally grounded AR design—supported by clear task structures, manageable route lengths, and motivationally balanced gamification—can strengthen cognitive learning while deepening visitors' immersion in real-world heritage contexts. Beyond these practical insights, the study contributes empirical evidence for age-aware AR interaction design and provides a replicable model for community-centered digital heritage interpretation. Future research should enhance accessibility features, explore generative AI for adaptive points of interest, and examine the longer-term socio-economic impacts of AR-mediated tourism on local artisan communities.

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Abbreviations

The following abbreviations are used in this manuscript:

AR	Augmented Reality
LBAR	Location-Based Augmented Reality
XR	Extended Reality
ICH	Intangible Cultural Heritage
PBOC	Pragmatic Behavior Observation Checklist
POI	Point(s) of Interest
LBGs	Location-Based Game(s)

Appendix A

Table A1. The User Engagement Scale Questionnaire.

Dimension	Questionnaire
Focused attention	The time I spent using AR game just slipped away.
	I was absorbed in this experience.
	I felt frustrated while using this AR game technology.
Perceived Usability	I found this AR game technology confusing to use.
	Using this AR game technology was taxing.
	I felt discouraged while using this AR game technology.
Aesthetic appeal	This AR game technology was attractive.
	This AR game technology was aesthetically appealing.
	This AR game technology appealed to my senses.
Reward	Using this AR game technology was worthwhile.
	My experience was rewarding
	I felt interested in these experiences

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