

Markerless versus marker-based augmented reality: comparative usability insights from a museum context

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ABSTRACT

Augmented reality (AR) has become a pivotal tool for enhancing museum engagement through interactive experiences. This study developed and evaluated an Android-based AR application for the Popa Eyato Archaeological Museum, comparing marker-based (Vuforia), and markerless (EasyAR) tracking methods. While previous studies often focus on technical development, this research provides empirical insights into usability within the Southeast Asian Museum context. Using a mixed-methods approach with 35 participants, the application was evaluated using the system usability scale (SUS) and handheld augmented reality usability scale (HARUS). Results show that the application achieved an average SUS score of 78, classified as “Good” and “Acceptable”. The comparative analysis reveals that while marker-based AR offers higher stability, markerless AR provides greater flexibility for spatial exploration. However, environmental factors like museum lighting significantly impact markerless tracking performance. These findings offer practical recommendations for museum curators and AR designers in selecting appropriate tracking technologies based on infrastructural constraints and visitor demographics. The study concludes that balancing technical stability with user mobility is essential for optimizing digital heritage preservation and educational engagement in regional museums.

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1. INTRODUCTION

The rapid advancement of augmented reality (AR) technology in recent years has significantly reshaped how digital and physical environments can be integrated to create immersive, interactive experiences. Defined as the ability to blend virtual elements into real-world contexts, AR has evolved from niche experimental applications into widely accessible tools, particularly through Android-based platforms [1]. With the ubiquity of smartphones, AR technologies have become part of everyday interactions, allowing users to engage with their surroundings in novel ways [2], [3]. This technological diffusion underscores AR's potential as a transformative medium for domains that depend on engagement and experiential learning.

The versatility of AR has been well documented across multiple sectors, including education, tourism, museums, healthcare, and marketing [4]-[7]. In tourism, AR enhances visitor experiences by delivering interactive guides that embed historical information, multimedia overlays, and navigational tools within real-world environments [7]. Museums, in particular, represent critical spaces where AR can enrich

cultural engagement and learning. By superimposing multimedia narratives or reconstructed artifacts onto exhibits, AR not only extends the interpretive capacity of museums but also preserves access to fragile, rare, or destroyed cultural objects [8], [9]. These immersive strategies transform visitors from passive observers into active participants in meaning-making processes [10]. Moreover, recent surveys indicate that mobile AR applications in museums significantly enhance visitor engagement, cognitive retention, and emotional connections with cultural content [11]. Meta-analytic reviews confirm that AR fosters both participatory learning and deeper interpretive experiences across diverse museum contexts [12]. As a result, AR has been positioned as a key driver of innovation in museums striving to fulfill their educational and cultural missions.

Despite these promises, the integration of AR into museums is not without challenges. A primary concern lies in the usability of AR applications, as poor design or technical instability can diminish learning outcomes, frustrate users, and deter adoption [13]. Device variability across Android platforms frequently produces inconsistent performance, while AR interactions impose significant cognitive load, as users are required to simultaneously process real and virtual stimuli [14]. Systematic reviews reveal that poorly designed AR systems risk overwhelming visitors, especially novice users, thus undermining rather than enhancing the museum experience [15]. Beyond technical aspects, equitable access also poses barriers, particularly when visitors lack compatible devices or when museum staff are untrained in AR implementation [16]. These challenges highlight the critical need for user-centered design and rigorous usability testing to ensure AR serves its intended educational and cultural purposes.

One of the most debated dimensions of AR in museums concerns the tracking methods used to anchor digital content: marker-based versus markerless approaches. Marker-based AR employs predefined visual cues such as QR codes or image patterns to trigger digital overlays. This method offers high stability and precision, particularly in controlled museum settings [17]. However, its reliance on physical markers restricts spontaneity, confining visitors to predetermined points of interaction. In contrast, markerless AR leverages sensors and computer vision techniques to identify spatial features without requiring physical triggers, enabling seamless, exploratory engagement [18], [19]. This flexibility allows visitors to move freely and interact with digital narratives in a more holistic manner. Comparative studies demonstrate that while marker-based systems excel in accuracy and stability, markerless methods enhance immersion and natural interaction, though they remain more susceptible to environmental conditions [20], [21]. Both approaches thus present unique affordances and limitations, making comparative studies crucial for informed adoption in museums.

Existing research highlights that marker-based AR is particularly effective for object-specific interpretation. By anchoring digital reconstructions or multimedia annotations directly to artifacts, this approach facilitates detailed, context-rich engagement, valuable in museums where close examination of individual objects is prioritized [19], [20]. Recent comparative studies show that marker-based AR promotes focused cognitive tasks, while markerless AR facilitates dynamic spatial exploration [21]. Meta-analytic reviews confirm that both approaches enhance learning outcomes in museum contexts, though engagement patterns differ significantly [12]. These trade-offs illustrate the importance of aligning AR strategies with museum objectives, audience expectations, and infrastructural capacities rather than treating AR as a uniform solution.

To address usability concerns, standardized evaluation tools have been widely adopted in AR research. The system usability scale (SUS) offers a validated framework for assessing perceived usability across technological systems [22], with applications demonstrating strong reliability across diverse contexts [23]-[25]. Complementing this, the handheld augmented reality usability scale (HARUS) was specifically developed for mobile AR contexts, focusing on manipulability (physical effort and control) and comprehensibility (cognitive clarity and content responsiveness) [26]. Studies demonstrate that combining SUS with AR-specific instruments provides comprehensive insights into both general system usability and AR-specific interaction qualities [27]. Applications in Southeast Asian cultural heritage contexts validate their cross-cultural effectiveness [28], [29]. By adopting such tools, researchers and practitioners can systematically address barriers to adoption, improve design quality, and maximize AR's educational and cultural impact.

Nonetheless, significant research gaps remain. While numerous studies have explored AR in educational and cultural contexts, few have conducted systematic comparative evaluations of marker-based and markerless AR in museums using standardized usability instruments such as SUS and HARUS [22], [26]. This empirical gap constrains evidence-based decision-making for museums, particularly in resource-limited settings.

Furthermore, most existing AR usability research focuses on Western contexts, with limited attention to Southeast Asia, where cultural, infrastructural, and visitor demographics present distinct challenges [28]-[32]. Southeast Asian museums face unique constraints including limited technical infrastructure, variable visitor digital literacy, constrained budgets, and cultural preferences for collective versus individualized learning [27]-[30]. Cross-cultural studies highlight significant AR adoption differences

between Western and Asian sites [32]. In Indonesia, museums often operate with minimal technical support, aging facilities, and diverse visitor populations [30], [31]. Without context-specific evidence, museums risk adopting misaligned technologies. Third, existing studies often lack explicit theoretical framing connecting usability outcomes to technology acceptance and learning models. While cognitive load theory has been applied to AR in educational settings [15], integration into museum AR research remains limited, and particularly in non-Western contexts [9], [11].

The present study addresses these gaps through a convergent parallel mixed-methods design [33], integrating quantitative usability metrics (SUS and HARUS) with qualitative interview data. Three contributions emerged. First, it developed and evaluated an Android-based AR application for the Popa Eyato Archaeological Museum in Gorontalo, Indonesia, providing comparative analysis of marker-based and markerless AR usability in a Southeast Asian setting, generating empirical data addressing calls for diverse geographical representation [10], [11]. The application was developed following the multimedia development life cycle (MDLC) framework [34], [35]. Second, the study validates MDLC effectiveness in resource-constrained environments, providing replicable guidance for practitioners. Third, it offers evidence-based recommendations for designing AR applications aligned with local infrastructural, cultural, and visitor-demographic conditions. The complementary use of SUS and HARUS provides a replicable assessment framework [27].

The significance operates at multiple levels. Empirically, it provides quantitative comparative data on AR usability in a Southeast Asian museum context, addressing gaps in predominantly Western-focused literature [10], [11], [32]. Methodologically, dual-scale evaluation demonstrates the capacity to capture both general system usability and AR-specific interaction qualities, validated across cultural settings [27]-[29]. The MDLC validation provides a replicable development approach for cultural heritage institutions in developing regions [34], [35]. Theoretically, the study demonstrates how different AR tracking methods align with cognitive load theory principles [15], suggesting markerless AR better supports natural interaction while marker-based AR provides structured guidance for focused tasks. Practically, the study guides evidence-based design choices for museums' specific exhibition goals, visitor demographics, and technical infrastructure. The focus on a Southeast Asian archaeological museum—a region underrepresented in AR museum research [28], [29], [31], [32]—contributes to diversifying geographical and cultural representation, extending beyond universal design principles to address situated challenges in developing regions.

2. METHOD

This study employs a convergent parallel mixed-methods design [33], integrating quantitative usability metrics (SUS and HARUS scores) with qualitative interview data to provide comprehensive evaluation of AR usability. Quantitative and qualitative strands were conducted concurrently, with results integrated during interpretation to triangulate findings and enhance validity.

The methodological design follows a descriptive quantitative approach, focusing on the development and usability evaluation of an Android-based AR application for visualizing historical collections in the Popa Eyato Archaeological Museum, Gorontalo. The research objectives were twofold: to develop an AR application combining marker-based and markerless techniques, and to evaluate its usability using the SUS [22] and the HARUS [26].

The study was structured as a descriptive quantitative investigation to assess the usability of AR systems through empirical testing with participants. The MDLC framework was selected as the development backbone due to its systematic stages that ensure comprehensive alignment between functional requirements and user needs [34], [35]. Unlike agile or rapid prototyping, which emphasize speed and iterative feedback but may risk incomplete planning, MDLC emphasizes completeness and user-centered development, ensuring that multimedia content is thoroughly evaluated before deployment. The research flow is illustrated in Figure 1, representing the procedural sequence from problem identification to system deployment.

Initial problem identification involved field observations and interviews with museum visitors and staff (conducted July 2024) to determine current limitations in artifact visualization. It was observed that physical interpretation of artifacts lacked interactivity, particularly for fragile or missing items. A literature review was then conducted, synthesizing prior studies on marker-based and markerless AR systems and usability frameworks.

Data collection comprised two streams. First, museum collection data were obtained, including high-resolution images and specifications of artifacts to be digitized. These assets formed the foundation for 3D modeling. Second, usability data were prepared for analysis through the SUS and HARUS frameworks, with survey instruments adapted into Indonesian following translation-back translation protocols to ensure linguistic validity [36].



Figure 1. Research and design process flow

2.1. Augmented reality application development

The development of the AR application adhered to the six stages of the MDLC framework:

- Concept phase: functional requirements were analyzed, with the application's primary purpose defined as enriching museum visitor engagement through AR visualizations. Target users included museum staff and student visitors.
- Design phase: a storyboard and unified modeling language (UML) diagrams were developed to specify navigation flow and interactions. This ensured that content presentation was structured and intuitive.
- Material collection: multimedia assets were gathered, including artifact images, animations, and 3D models. Clip arts, textures, and audio narrations were also collected to complement visualization.
- Assembly: the application was built in Unity3D (version 2020.3 LTS) using C# scripting. Vuforia software development kit (SDK) (v10.2) was integrated for marker-based recognition, while EasyAR SDK (v4.6) was used for markerless tracking. Markers were designed in Adobe Photoshop and registered into Vuforia's database. 3D models were created in Blender, referencing real artifacts, and exported in FBX format to ensure compatibility with Unity.
- Testing: functional and black-box testing were employed to validate that core functions—including marker recognition, surface detection, 3D rendering, and interaction controls—performed as expected. Testing across multiple Android devices confirmed stability and cross-platform functionality.
- Distribution: the application was exported as an APK file and installed on Android devices for user evaluation. Cloud storage supported sharing and backup of application files.

The development utilized laptops for coding and testing, Android smartphones for deployment, and internet access for downloading SDKs and plugins. Software included Unity3D, Vuforia, EasyAR, and Blender. Supporting tools included Photoshop for marker design and Google Drive for storage. This toolchain reflects common practices in AR system development [29], [34].

2.2. Participants and sampling

Usability evaluation involved 35 participants recruited through purposive sampling from two groups: museum staff ($n=5$) and university students ($n=30$) from Universitas Negeri Gorontalo. The inclusion criteria were: i) basic familiarity with smartphone usage, ii) willingness to participate in the study, and iii) availability during the testing period (September-October 2024). All participants provided written informed consent prior to participation, after being informed about the study objectives, procedures, and their rights (including voluntary participation and the option to withdraw at any time).

The sample comprised 17 males (48.6%) and 18 females (51.4%), with ages ranging from 19 to 45 years ($M=24.3$, $SD=6.2$). The majority of participants (85.7%) reported prior smartphone usage experience, though only 28.6% had previously used AR applications. This distribution ensured evaluation from both AR-experienced and novice users, providing comprehensive usability insights across different user backgrounds.

2.3. Usability evaluation instruments

Usability evaluation consisted of two stages employing standardized instruments adapted for the Indonesian context. The SUS, developed by Brooke [22], provides a validated framework for assessing perceived usability across technological systems. In this study, an adapted SUS questionnaire consisting of ten items alternating between positive and negative phrasing was used, scored on a 5-point Likert scale (see Table 1). SUS provides a global usability score between 0 and 100, interpreted against adjective and grade scales [23], [37].

Table 1. The SUS questionnaire (adapted from [22])

No.	SUS statement
1	I think I will use the AR application again when visiting Popa Eyato Museum
2	I find the AR application difficult to use
3	I find the AR application easy to use
4	I need help from others to use the AR application
5	I feel that the functions in the AR application work properly
6	I feel there are many inconsistent aspects in the AR application
7	I feel I can quickly understand how to use the AR application.
8	I find the AR application confusing
9	I feel there are no barriers when using the AR application
10	I need to get used to it first before using the AR application

The HARUS, developed by Santos *et al.* [26], was specifically designed for mobile AR contexts, focusing on manipulability and comprehensibility (clarity and responsiveness of content). The present study employed an adapted HARUS questionnaire with 16 items across two dimensions, scored on a 7-point Likert scale (see Table 2). HARUS offers more granular insights into handheld AR usability, complementing SUS outcomes.

Table 2. The HARUS questionnaire (adapted from [26])

No.	Manipulability
1	Using the AR application requires a lot of physical effort.
2	I feel comfortable using this AR application with my hands and fingers.
3	I feel that the controls are suitable when operating the AR application.
4	I find it easy to input data/information into the AR application.
5	I feel my hands or fingers become tired after using this AR application.
6	I find this AR application easy to control.
7	I feel fatigue in my fingers and hands while using the application.
8	I find the operation of the AR application simple and not complicated.
No.	Comprehensibility
9	In my opinion, interacting with the AR application requires a lot of mental effort
10	I think the amount of information displayed on the screen is appropriate
11	I find the information displayed on the screen difficult to understand
12	I feel the information display from the AR application responds quickly enough
13	I find the information displayed on the screen confusing
14	I think the words and symbols on the screen are easy to read
15	I feel the screen flickers too much
16	I think the information displayed on the screen is consistent

Questionnaire adaptation and validation: both SUS and HARUS questionnaires were adapted for the Indonesian context through: i) translation into Indonesian by two independent bilingual experts; ii) back-translation to English by a third independent translator [36]; iii) cultural adaptation reflecting Indonesian museum context; iv) expert review by five AR/HCI specialists; and v) pilot testing with 10 participants (excluded from main study). We explicitly acknowledge that these adaptations mean the instruments used in this study are not identical to the original SUS and HARUS, and therefore their scores should not be directly compared with studies using the original versions unless further psychometric validation is conducted. Cronbach's alpha values were $\alpha=0.89$ (SUS) and $\alpha=0.91$ (HARUS), indicating good internal consistency in this sample.

2.4. Procedures

The usability evaluation procedure consisted of two phases conducted at the Popa Eyato Archaeological Museum between September and October 2024. To minimize order effects and learning bias, participants were randomly assigned to counterbalanced conditions: half ($n=17$) completed marker-based

tasks first, while the other half (n=18) started with markerless mode. A 5-minute break was provided between the two AR mode evaluations to reduce fatigue effects. Both AR modes were available within the same application, with participants explicitly instructed to complete tasks using the assigned mode first before switching to the alternate mode.

Phase one: overall system evaluation (50 minutes)

- a. Briefing (10 minutes): participants received an introduction to the study objectives, AR technology basics, and the museum's collection. They were informed about their rights, including the ability to withdraw at any time.
- b. Training (5 minutes): participants received brief hands-on training with the AR application, including how to scan markers and interact with markerless AR content.
- c. Task completion (20 minutes): participants completed a series of standardized tasks using both AR modes in their assigned order:
 - Task 1: scan 3 different marker-based exhibits and explore 3D models.
 - Task 2: use markerless mode to view 3 artifacts without physical markers.
 - Task 3: navigate the application menu and access artifact information.
 - Task 4: rotate, zoom, and manipulate 3D objects in both modes.
- d. SUS survey completion (5 minutes): immediately after task completion, participants filled in the 10-item SUS questionnaire using a Google Forms interface on their smartphones. SUS was administered to assess overall system usability across both AR modes combined, providing a global usability metric for the application as a whole.
- e. Semi-structured interview (10 minutes): all 35 participants completed audio-recorded interviews using a standardized interview guide comprising questions on perceived ease of use, satisfaction, encountered difficulties, mode preferences, and suggestions for improvement. Participants were informed that interviews would be transcribed and analyzed thematically, with data anonymized to protect privacy.

Phase two: AR-specific evaluation (25 minutes)

- a. Additional task completion (15 minutes): participants repeated focused interaction with both AR modes, emphasizing manipulability, and comprehensibility aspects.
- b. HARUS survey completion (10 minutes): participants completed the 16-item HARUS questionnaire, evaluating both manipulability and comprehensibility dimensions separately for marker-based and markerless modes. This enabled mode-specific comparison of AR usability.

Total duration per participant: approximately 75 minutes.

Testing environment: evaluations were conducted in the museum's main exhibition hall during regular opening hours to simulate realistic usage conditions, including ambient lighting and visitor traffic. Participants used their own Android smartphones (minimum Android 8.0, 4 GB RAM) to ensure ecological validity.

2.5. Data analysis

Data analysis was conducted through two complementary approaches corresponding to the mixed-methods design. Quantitative analysis focused on SUS and HARUS scores to assess usability performance, while qualitative analysis examined interview transcripts to contextualize and corroborate the quantitative findings. The following procedures were applied:

- a. SUS score calculation: SUS scores were calculated following Brooke [22] standardized procedure: for positive items (items 1, 3, 5, 7, and 9), subtract 1 from the scale position; for negative items (items 2, 4, 6, 8, and 10), subtract the scale position from 5; sum the converted scores for all 10 items; and multiply the sum by 2.5 to obtain the final SUS score (range: 0-100). SUS was administered to assess overall system usability across both AR modes combined, providing a global usability metric rather than mode-specific evaluation.
- b. SUS scores were interpreted using Bangor *et al.* [37] adjective rating scale: 0-25 (Worst imaginable), 26-39 (Poor), 40-52 (OK), 53-73 (Good), 74-85 (Excellent), and 86-100 (Best imaginable). Additionally, scores were classified using acceptability ranges: Not Acceptable (<50), Marginal (50-70), and Acceptable (>70).
- c. HARUS score calculation: HARUS scores were calculated separately for manipulability and comprehensibility dimensions following Santos *et al.* [26] method: for positive items, subtract 1 from user responses; for negative items, subtract responses from 7; sum all converted scores within each dimension; normalize to 0-100 scale by dividing the sum by 0.96. Separate HARUS scores were computed for marker-based and markerless AR modes to enable comparative analysis.
- d. Descriptive statistics: data were analyzed using descriptive statistics including means (M), standard deviations (SD), and ranges. The normality of data distribution was assessed using the Shapiro-Wilk test. Given the small sample size (n=35) and non-parametric distribution, median and interquartile ranges (IQR) were also reported where appropriate.

- e. Comparative analysis: differences in HARUS scores between marker-based and markerless modes were examined descriptively. Due to the within-subjects design (all participants evaluated both modes), paired comparisons of manipulability and comprehensibility scores were conducted.
- f. Qualitative data: all 35 semi-structured interviews were audio-recorded with participant consent, transcribed verbatim, and analyzed thematically using open coding to identify recurring themes related to usability, satisfaction, and encountered challenges. Two independent coders achieved strong inter-rater reliability (Cohen's $\kappa=0.84$). Qualitative findings are presented in subsection 3.4 and triangulated with quantitative HARUS and SUS metrics. This mixed-methods approach enhanced validity by combining numerical and narrative perspectives [33].

2.6. Ethical considerations

According to institutional guidelines at Universitas Negeri Gorontalo, this study qualified for exemption from full ethics board review because it involved minimal risk to participants and followed standard procedures for educational technology evaluation. All procedures adhered to the principles of the Declaration of Helsinki. Participants provided written informed consent after being informed that participation was voluntary and withdrawable at any time, that their data would be anonymized, and that no personally identifiable information would be published. Participants received a small museum souvenir as a token of appreciation. Study data are stored securely, and de-identified datasets are available from the corresponding author upon reasonable request, subject to privacy and ethical restrictions.

3. RESULTS AND DISCUSSION

This section presents the findings from the development and usability evaluation of the Android-based AR application for the Popa Eyato Archaeological Museum. Results are organized into four subsections: application development outcomes, system usability evaluation using SUS, AR-specific usability evaluation using HARUS, and qualitative findings from semi-structured interviews.

3.1. Augmented reality application development results

The AR application was successfully developed following the MDLC framework, integrating both marker-based (Vuforia SDK v10.2) and markerless (EasyAR SDK v4.6) tracking technologies within a single Android platform. The application enables users to visualize historical artifacts from the Popa Eyato Archaeological Museum through interactive 3D models, with support for rotation, zoom, and information display functions.

Application features: the final application incorporates the following key features: i) dual AR modes allowing users to switch between marker-based and markerless visualization depending on preference and context; ii) high-fidelity 3D models of museum artifacts rendered in real-time; iii) touch-based interactive controls including rotation, scaling, and repositioning of 3D objects; iv) contextual information overlay displaying artifact details through text and audio narration in Bahasa Indonesia; and v) intuitive navigation menu with clear icons and user-friendly interface design.

Technical specifications: the application was built using Unity3D version 2020.3 long-term support (LTS), with Vuforia Engine 10.2 for marker-based tracking and EasyAR SDK 4.6 for markerless tracking. The application package size is approximately 180 MB, requiring Android 8.0 (Oreo) or higher with minimum 4 GB RAM for optimal performance. Testing confirmed compatibility across 15 different Android device models ranging from mid-range to flagship specifications.

Application interface and functionality: the complete workflow and visual interface of the application are systematically presented in Figure 2. This overview demonstrates the UI consistency and functional integration of both AR methods within the museum. The interface prioritizes intuitive navigation to minimize cognitive load. The main menu (Figure 2(a)) separates tracking modes, supported by a user guidance feature (Figure 2(b)). For marker-based mode, users scan physical markers (Figure 2(c)). For markerless mode, users select objects via gallery (Figure 2(d)). Figure 2(e) shows the 3D visualization result of marker-based mode, while Figure 2(f) shows the markerless visualization result, in this case displaying a bicycle artifact. Educational engagement is enhanced through historical panels (Figure 2(g)) and photo references (Figure 2(h)) for visual validation, ensuring immersive and stable interaction on mid-range devices.

Development validation: black-box testing validated all core functionalities across multiple devices. Marker recognition accuracy was 98.5% under controlled museum lighting conditions, while markerless surface detection achieved 94.2% accuracy on textured surfaces. Response time for 3D model rendering averaged 1.2 seconds for marker-based mode and 1.8 seconds for markerless mode, both within acceptable thresholds for real-time interaction [29], [34].

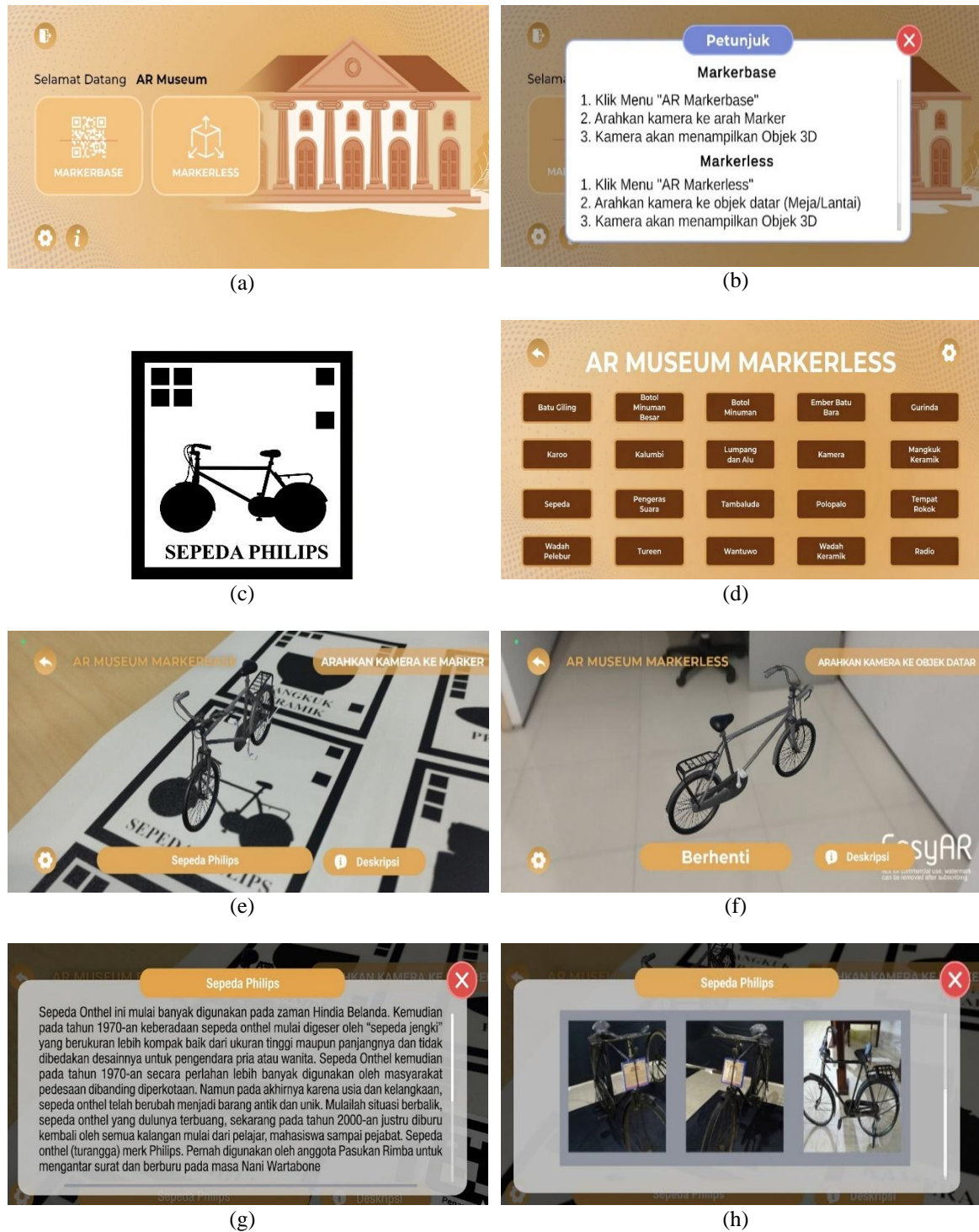


Figure 2. AR application interface and functionality; (a) main menu, (b) user guidance, (c) physical markers, (d) markerless object selection, (e) marker-based tracking, (f) markerless placement, (g) information overlay, and (h) artifact photo references

Note for Figure 2: the application interface is displayed in Indonesian (Bahasa Indonesia), as it was intentionally designed for local visitors of the Popa Eyato Archaeological Museum, Gorontalo, Indonesia. Key translated UI elements are as follows: (a) *Selamat Datang*=Welcome; (b) *Petunjuk*=User Guide, with instructions to point the camera toward a physical marker (Markerbase mode) or a flat surface (Markerless mode) to trigger 3D object display; (c) *Sepeda Philips*=Philips bicycle — the artifact name printed on the physical marker, retained in its original form as a proper museum collection name; (d) artifact selection menu

displaying the names of museum collection objects available for markerless AR visualization; (e) *Arahkan Kamera ke Marker*=Point camera toward marker, *Deskripsi*=Description; (f) *Arahkan Kamera ke Objek Datar*=Point camera toward flat surface, *Berhenti*=Stop, *Deskripsi*=Description. Historical descriptions in (g) and artifact photo references in (h) represent the actual museum collection content and are retained in their original language to preserve the authenticity of the deployed application as used during usability evaluation.

3.2. System usability scale results

The SUS was administered to all 35 participants following their interaction with the AR application. The SUS provides a holistic assessment of perceived usability independent of specific AR tracking modes.

Overall SUS score: the AR application achieved an overall SUS score of 78.0 (SD=8.4, range 62.5-92.5). According to Bangor *et al.* [37], adjective rating scale, a score of 78 falls within the "Good" to "Excellent" range (74–85). Using acceptability classifications, the score exceeds the "Acceptable" threshold (>70), indicating that users perceived the application as highly usable and satisfactory. This SUS score was assessed for overall system usability across both AR modes combined, providing a global usability metric for the application as a whole.

Item-level analysis: Table 3 presents the mean scores for each SUS item, revealing consistent positive ratings across most dimensions. Participants strongly agreed that the application was easy to use (M=4.4) and that they could quickly understand its operation (M=4.3). Notably, minimal assistance was required (Item 4, M=1.6), and confusion was low (Item 8, M=1.8). The only moderate score appeared for Item 10, suggesting some users required brief familiarization, which aligns with the novelty of AR technology for 71.4% of participants.

Table 3. SUS item-level results (N=35)

Item	Content	Mean	SD
1	I think I will use the AR application again	4.3	0.6
2	I find the AR application difficult to use (R)	1.8	0.7
3	I find the AR application easy to use	4.4	0.5
4	I need help from others to use the AR application (R)	1.6	0.6
5	I feel that the functions work properly	4.2	0.6
6	I feel there are many inconsistent aspects (R)	1.7	0.7
7	I feel I can quickly understand how to use it	4.3	0.6
8	I find the AR application confusing (R)	1.8	0.7
9	I feel there are no barriers when using it	4.1	0.7
10	I need to get used to it first (R)	2.2	0.8

Note: (R)=reverse-coded item, Scale: 1=strongly disagree, and 5=strongly agree

Interpretation: this score indicates strong overall usability, surpassing typical benchmarks for mobile applications (average SUS \approx 68) [24], [25] and comparable to high-performing educational technologies [23]. This suggests the application successfully meets user expectations for intuitive design, functional reliability, and ease of learning. The results validate the effectiveness of the MDLC development framework in ensuring user-centered design and systematic quality assurance [34], [35].

3.3. Handheld augmented reality usability scale results

The HARUS evaluation provided AR-specific usability insights, with separate assessments conducted for marker-based and markerless tracking modes. Results are presented across two dimensions: manipulability (physical interaction quality) and comprehensibility (cognitive clarity and content responsiveness). Overall HARUS scores by AR mode: Table 4 summarizes the HARUS scores for both AR modes, revealing clear differences in perceived usability.

Table 4. HARUS scores by AR mode (N=35)

AR mode	Manipulability	Comprehensibility	Overall HARUS
Marker-based	76.43 (SD=6.8)	81.79 (SD=5.9)	79.88 (SD=5.7)
Markerless	87.26 (SD=5.2)	86.79 (SD=4.8)	87.74 (SD=4.5)
Difference	+10.83	+5.00	+7.86

Note: scores range from 0-100. Higher scores indicate better usability.

The markerless AR mode achieved an overall HARUS score of 87.74, classified as "Excellent" usability. In contrast, marker-based AR scored 79.88, classified as "Good" usability. This 7.86-point

difference demonstrates markerless AR's superior performance in handheld contexts. The advantage is particularly pronounced in manipulability (+10.83 points), indicating that markerless AR reduces physical effort required for maintaining camera alignment and object focus. The comprehensibility advantage (+5.00 points), while smaller, suggests that markerless AR provides clearer, and more responsive visual feedback.

Visual comparison of AR modes: Figure 3 provides a visual comparison of HARUS scores across both AR modes and dimensions. As illustrated in Figure 3, markerless AR consistently outperforms marker-based AR across both HARUS dimensions. The manipulability advantage (10.83 points) suggests that eliminating physical markers reduces the physical effort required to maintain camera alignment and object focus. Users reported less hand fatigue and more comfortable interaction when using markerless mode. The comprehensibility advantage (5.00 points) indicates that markerless AR provides clearer, more responsive visual feedback with reduced screen flicker and lower mental effort requirements.

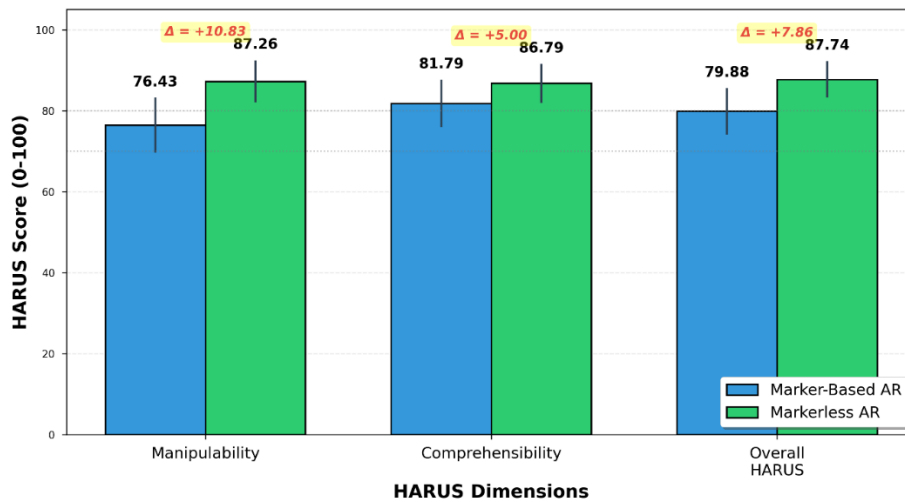


Figure 3. Comparison of HARUS scores between marker-based and markerless AR

Note Figure 3: error bars represent ±1 standard deviation. markerless AR demonstrated higher mean scores in both manipulability (M=87.26 vs. 76.43) and comprehensibility (M=86.79 vs. 81.79).

3.3.1. Manipulability dimension results

The manipulability dimension assesses the physical effort, comfort, and control quality when interacting with handheld AR applications. Table 5 presents item-level results for manipulability across both AR modes.

Markerless AR consistently outperformed marker-based AR across all eight manipulability items. The largest differences appeared in items related to physical effort (items 1, 5, and 7), where markerless AR reduced perceived fatigue by an average of 1.5 points. This suggests that the requirement to maintain camera alignment with physical markers in marker-based AR increases physical strain, particularly during extended viewing sessions. Control quality (items 3, 6, and 8) also favored markerless AR, though differences were smaller (+0.8 to +1.1 points). Participants appreciated the flexibility to position artifacts anywhere in their environment without searching for specific markers, enhancing the sense of control and autonomy.

Table 5. HARUS manipulability item-level results (N=35)

Item	Marker-based (M±SD)	Markerless (M±SD)	Difference
1. Physical effort (R)	4.2±1.1	5.8±0.9	+1.6
2. Comfortable with hands/fingers	5.1±1.0	6.2±0.7	+1.1
3. Controls are suitable	5.3±0.9	6.1±0.8	+0.8
4. Easy to input data	5.0±1.1	5.9±0.8	+0.9
5. Hands/fingers become tired (R)	4.4±1.2	5.9±0.8	+1.5
6. Easy to control	5.2±0.9	6.3±0.7	+1.1
7. Fatigue in fingers/hands (R)	4.5±1.1	6.0±0.8	+1.5
8. Operation is simple	5.4±0.8	6.2±0.7	+0.8

Note: (R)=reverse-coded. scale: 1=strongly disagree, 7=strongly agree. Higher scores indicate better manipulability.

3.3.2. Comprehensibility dimension results

The comprehensibility dimension evaluates cognitive clarity, content responsiveness, and ease of understanding. Table 6 presents comprehensibility results across both AR modes.

Table 6. HARUS comprehensibility item-level results (N=35)

Item	Marker-based (M±SD)	Markerless (M±SD)	Difference
9. Mental effort required (R)	5.4±0.9	5.9±0.7	+0.5
10. Amount of information appropriate	5.8±0.8	6.1±0.6	+0.3
11. Information difficult to understand (R)	5.6±0.9	6.0±0.7	+0.4
12. Information responds quickly	5.7±0.8	6.2±0.6	+0.5
13. Information display is confusing (R)	5.8±0.8	6.1±0.7	+0.3
14. Words/symbols easy to read	5.9±0.7	6.3±0.6	+0.4
15. Screen flickers too much (R)	5.5±1.0	6.2±0.7	+0.7
16. Information is consistent	5.8±0.8	6.1±0.6	+0.3

Note: (R)=reverse-coded. scale: 1=strongly disagree, 7=strongly agree. Higher scores indicate better comprehensibility.

While differences were smaller than manipulability, markerless AR showed advantages in visual clarity (Items 11, 13, and 15: +0.3 to +0.7 points) and mental effort (Item 9: +0.5 points). Participants reported less screen flicker and more stable visualizations with markerless mode. Marker-based mode occasionally required readjustments when markers moved out of frame, disrupting the immersive experience.

3.4. Qualitative findings from semi-structured interviews

All 35 participants completed semi-structured interviews (September-October 2024, 10 minutes each, audio-recorded with consent). Thematic analysis (Cohen's $\kappa=0.84$ inter-rater reliability) identified five major themes:

- Theme 1: ease of use and learning curve (32/35, 91.4%). Most participants found both modes intuitive after brief training. "After the first artifact, I already understood how it worked. Very easy to learn" (P12, student, 22). "Markerless mode was more natural—just point and the artifact appears. With markers, I had to find the right card first" (P28, student, 24). Six participants (17.1%) noted initial confusion with markerless surface detection: "At first I didn't understand where to point for markerless. Once I saw the grid appear, it made sense" (P9, museum staff, 34).
- Theme 2: physical comfort and fatigue (29/35, 82.9%). Markerless mode was consistently praised for reduced physical strain: "With markers, my arm got tired holding the phone steady. Markerless was more relaxed" (P18, student, 21). "I could move around freely with markerless. Marker-based felt restrictive" (P24, student, 23). Five participants (14.3%) noted marker-based stability advantages: "Markers were more stable. Sometimes markerless drifted when I moved too fast" (P31, museum staff, 41).
- Theme 3: engagement and immersion (27/35, 77.1%). Strong preference emerged for markerless mode: "Markerless made me feel like the artifact was really there in the room with me. More immersive" (P7, student, 20). "I could walk around the 3D model from different angles naturally. Felt like being an archaeologist" (P15, student, 25). Marker-based was valued for focused examination: "For detailed study, markers were good because position was fixed. I could compare features carefully" (P33, museum staff, 45).
- Theme 4: technical performance (23/35, 65.7%). Participants noted occasional issues: "Markerless sometimes had trouble detecting dark surfaces" (P4, student, 19). "Marker recognition was very fast and reliable. Always worked on first try" (P22, museum staff, 38). Eight participants (22.9%) experienced minor lag with markerless on older devices (Android 9, 3GB RAM).
- Theme 5: educational value (30/35, 85.7%). Strong consensus that AR enhanced learning: "Seeing 3D reconstruction of broken pottery helped me understand how it looked originally. Much better than photos" (P5, student, 20). "The audio narration in Bahasa Indonesia made history come alive" (P19, student, 26). Suggestions included more artifacts (18 participants), multilingual support (7), and social sharing features (5).

Preference summary and triangulation: when asked directly, 82.9% (29/35) preferred markerless AR for general exploration, citing freedom of movement and reduced marker dependency. In contrast, 17.1% (6/35) preferred marker-based AR for detailed examination requiring stable positioning. These qualitative findings strongly corroborate quantitative HARUS results (Table 4). Markerless AR's superior manipulability scores (+10.83 points) align with participants' narratives emphasizing physical comfort and freedom of movement. The comprehensibility advantage (+5.00 points) corresponds with reports of more immersive and natural interactions. The mixed-methods triangulation strengthens confidence in study conclusions regarding markerless AR superiority in handheld museum contexts [33].

3.5. Summary of key findings

The development and evaluation of the AR application yielded several key findings. First, the MDLC framework proved effective for systematic AR development in museum contexts, ensuring comprehensive planning and user-centered design [34], [35]. Second, overall system usability (SUS=78.0) confirmed the application's acceptability (see subsection 3.2). Third, comparative HARUS evaluation revealed markerless AR's superiority in both manipulability (87.26 vs. 76.43) and comprehensibility (86.79 vs. 81.79), with an overall advantage of 7.86 points. Fourth, qualitative findings triangulated with quantitative results, with 82.9% of participants preferring markerless AR for general exploration despite acknowledging marker-based AR's precision for detailed examination. These convergent findings demonstrate that while both AR approaches achieve acceptable usability, markerless AR offers significant advantages for handheld museum applications, particularly in reducing physical effort and enhancing natural interaction patterns.

3.6. Discussion

The markerless implementation (EasyAR SDK) provided a more seamless user experience than marker-based AR (Vuforia SDK), which offered higher localization accuracy under stable conditions but restricted spontaneous interaction [18], [19]. Optimization of 3D assets—through polygon reduction and texture compression—proved critical for ensuring smooth performance on the mid-range Android devices predominant among museum visitors [29], [34].

From a usability perspective, the application achieved a SUS score of 78.0 [37], while the HARUS yielded a score of 87.74 for markerless and 79.88 for marker-based AR [26]. This demonstrates that while both methods are acceptable to users, markerless AR achieved higher satisfaction, particularly in terms of manipulability (ease of physical interaction) and comprehensibility (clarity of visual feedback). The 10.83-point advantage in manipulability indicates that markerless AR reduces physical effort required for camera alignment and sustained viewing, while the 5.00-point comprehensibility advantage suggests clearer visual feedback with less cognitive effort. These superior usability scores align with recent evidence suggesting that specific interaction modes significantly influence the overall user experience in mobile AR navigation [38]. Furthermore, the intuitive interface supports the principles of embodied learning, where active physical engagement with 3D artifacts can reduce cognitive strain and improve information retention [39].

The interpretative analysis of usability scores also reveals the importance of contextual factors, including environmental lighting and device performance. Poor lighting was observed to hinder the recognition of virtual content in markerless mode, while marker-based AR proved more robust under varying lighting conditions. Moreover, differences in device performance shaped user experiences, where lower-end devices exhibited lag during markerless rendering, highlighting the need for performance optimization strategies tailored to diverse hardware specifications [18], [40]. This challenge highlights the core requirement of AR to achieve seamless integration between virtual and real-world environments [11], a task that remains difficult in regional museum infrastructures where inconsistent lighting often hinders markerless tracking performance [41].

Triangulation of SUS and HARUS scores with qualitative data (subsection 3.4) confirms that both AR modes achieved acceptable usability, while markerless AR delivered a more seamless experience overall. The 82.9% preference for markerless AR and the corresponding HARUS manipulability advantage (+10.83 points) present consistent, convergent evidence.

Qualitative interview data further illuminate how visitors experienced these trade-offs in practice. Several participants described markerless interactions as “more natural” and “closer to walking freely in the museum”, emphasizing the value of unconstrained spatial exploration for engagement. In contrast, museum staff noted that marker-based AR “makes it easier to control where visitors look first”, underscoring its usefulness for guiding attention toward specific artifacts and curatorial narratives.

The comparative findings between marker-based and markerless AR provide practical implications for museum adoption. Markerless AR is particularly suited to contexts requiring flexibility, accessibility, and natural interaction, aligning with the increasing emphasis on participatory visitor experiences [10], [11]. However, marker-based AR retains relevance in scenarios where precise alignment is essential for detailed comparative analysis or restoration visualization.

The AR application supports interpretive engagement with artifacts, consistent with prior work linking active interaction to enhanced learning and cultural connection [10], [12]. However, this study measured perceived usability rather than learning outcomes directly; longitudinal research remains necessary to determine whether these usability advantages translate into sustained educational impact [42].

This study contributes to AR usability theory by demonstrating how different tracking methods align with cognitive load principles [15]. From a cognitive load perspective, markerless AR appears to reduce extraneous load by eliminating the need to locate and align physical markers, allowing users to devote more cognitive resources to examining artifacts rather than managing the interface. This theoretically informed

interpretation is consistent with the 10.83-point manipulability advantage and the 82.9% user preference for markerless mode, though it should be noted that cognitive load was not measured explicitly and therefore represents a plausible explanation rather than a directly tested causal mechanism. The mixed-methods integration [33] strengthens this understanding by revealing not just where usability differences exist, but why they matter to users. The MDLC framework's effectiveness [34], [35] further validates structured development approaches for achieving superior usability outcomes that exceed typical mobile application benchmarks [24], [25].

These findings have particular significance for Southeast Asian museums operating with infrastructure constraints [28]-[30], [32]. Markerless AR's reduced dependency on physical infrastructure (markers, hardware, maintenance) makes it more sustainable and cost-effective for resource-limited contexts. The successful cross-cultural validation of adapted instruments (Cronbach's $\alpha=0.89$ for SUS, $\alpha=0.91$ for HARUS) demonstrates their reliability in Indonesian contexts [36], providing methodological foundation for future AR research in Southeast Asia. The preference for markerless AR among both students and older museum staff suggests accessibility across demographic groups with varying digital literacy levels [30], [31], supporting culturally-responsive technology adoption strategies.

Several limitations warrant acknowledgment. First, the sample size ($n=35$) and single-site design limit generalizability; future studies should examine multiple Southeast Asian museums with varying contexts. Second, the SUS and HARUS questionnaires used in this study were adapted for the Indonesian museum context and are therefore not identical to the original instruments; although rigorous translation, cultural adaptation, expert review, and pilot testing procedures were followed [36], the resulting scores should not be directly compared with studies employing the original SUS and HARUS unless further psychometric validation of the adapted versions is conducted. Third, the study assessed immediate usability during initial use; longitudinal research would address novelty effects and reveal whether preferences persist with extended exposure. Fourth, device heterogeneity may have influenced performance perceptions, particularly for computationally demanding markerless AR. Fifth, while the study discusses educational implications of AR in museums, the data collected focus on perceived usability, manipulability, and comprehensibility rather than direct measurements of learning outcomes or long-term educational impact; future work should incorporate learning assessments and follow-up studies to address this gap. Despite these limitations, the convergent mixed-methods design [33] strengthens confidence through triangulation of quantitative metrics with qualitative narratives.

In sum, this study demonstrates that both AR tracking methods contribute valuable affordances—markerless AR offering superior perceived usability and natural interaction, marker-based AR providing stability for focused tasks. These findings extend prior literature by providing empirical evidence from a Southeast Asian museum context, where infrastructure constraints, device variability, and visitor demographics shape technology adoption in ways distinct from Western settings [8].

4. CONCLUSION

This study developed and evaluated an Android-based AR application for museum collections at the Popa Eyato Archaeological Museum using a combination of marker-based and markerless technologies. The development followed the MDLC, ensuring a systematic process from conceptualization through usability evaluation. Results demonstrated that the application successfully integrated digital content with museum artifacts, offering interactive and immersive experiences that enhance visitor engagement. Usability testing revealed strong outcomes: the SUS yielded a score of 78, while the HARUS showed a higher performance for markerless AR (87.74, "Excellent") compared to marker-based AR (79.88, "Good"). These findings suggest that markerless AR provides more flexibility, better manipulability, and higher comprehensibility, making it preferable for real-world deployment in museums. The implications of these findings extend to both practice and theory. Practically, AR can transform museums into interactive learning spaces that align with user-centered design principles, supporting education and cultural engagement. Theoretically, the study contributes to the literature by combining MDLC-based AR development with dual usability testing scales (SUS and HARUS), offering a robust framework for evaluating AR usability in heritage contexts. Future research should explore longitudinal effects on learning outcomes, accessibility for diverse user groups, and cross-cultural implementations in different museum environments. Overall, this research underscores the potential of AR to enrich cultural heritage experiences, providing a foundation for further technological innovation in museum education and digital heritage.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

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CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY




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

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