Enhancing Architectural Heritage Engagement: A Comparative Study of a WebGL and Spatially-Aware AI-Guided Immersive Environment

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Abstract: This study investigates the impact of a spatially-aware AI-guided immersive environment on architectural heritage engagement. A controlled experiment was conducted with 20 final-year Bachelor of Architectural Studies students, comparing a WebGL-based 360° virtual tour of Murray House, Hong Kong, enhanced by a Deep Seek AI-powered guide, against a traditional 360°-only tour. The AI system provided real-time, context-aware guidance by tracking user position and viewing direction, enabling dynamic interactions such as directing attention to specific architectural features. Quantitative results revealed significant improvements in the AI-guided group, including higher navigation comprehensiveness (90% vs. 60% of nodes visited). Survey data indicated elevated perceived engagement, learning, and satisfaction. Qualitative feedback highlighted the AI's role in facilitating guided discovery and contextual dialogue, transforming passive observation into active inquiry. The findings demonstrate that integrating spatially-aware AI into web-based immersive environments significantly enhances engagement and educational value, offering a scalable model for future heritage education tools. Limitations include the use of an untrained AI model and mobile browser access, with future research targeting AI fine-tuning and VR headset integration.

Keywords: Architectural heritage engagement, AI-guided interaction, 360° immersive environment, spatial awareness, virtual heritage education.

1. INTRODUCTION

The digital preservation and interpretation of cultural heritage have undergone a profound transformation with the advent of immersive media technologies. Platforms leveraging WebGL have democratized access to high-fidelity, three-dimensional representations of heritage sites, allowing for browser-based exploration without the need for specialized hardware (Kim, *et al*. 2022). Concurrently, 360° panoramic photography has emerged as a cost-effective and efficient method for creating authentic, immersive visual experiences, capturing the spatial essence and materiality of architectural environments (Rodriguez-Garcia, *et al*. 2022; Argyriou, *et al*. 2020). While these technologies have successfully moved beyond static imagery, the user experience often remains largely passive, limiting the potential for deep, contextual learning and engagement (Meier, *et al*. 2024).

This passivity presents a particular challenge in specialized education, such as architecture. For architectural students, understanding a heritage site extends beyond visual appreciation to encompass the comprehension of spatial sequences, structural logic, material properties, and historical construction techniques. Traditional virtual tours, often composed of linked 360° images, provide a sense of presence but frequently lack the contextual depth and interactive dialogue necessary to foster this level of analytical understanding. The emergence of sophisticated generative Artificial Intelligence (AI) models, accessible via API, offers a novel solution. An AI-powered conversational agent can act as an intelligent tour guide (Carrasco-García, *et al*. 2025; Nie, *et al*. 2025), capable of providing instant, context-aware information and answering spontaneous, user-driven queries, thereby transforming a static visual experience into a dynamic, interactive learning session (Tuomi, *et al*. 2025; Carvalho and Ivanov, 2024).

However, the integration of such AI guides within a real-time WebGL environment for architectural heritage education remains an underexplored area. Previous research has often focused on either the technological development of virtual environments or the capabilities of AI in isolation. There is a lack of empirical, user-centered studies that quantitatively and qualitatively measure the impact of this integration on the engagement and learning outcomes of specific user groups, such as architecture students. This group requires not just information, but a deep, spatial-dialogic interaction with the subject matter.

To address this gap, this paper presents a controlled experiment evaluating a web-based application that integrates WebGL-rendered 360° panoramas with an AI tour guide (powered by the Deep

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Seek API) against a control environment of pure 360° photos. The study was conducted with 20 architectural students to investigate the specific value-added of the AI-driven interactive component. The research is guided by the following questions:

1. RQ1: How does an AI tour guide impact behavioral and cognitive engagement in a virtual heritage tour?

2. RQ2: What are the perceived benefits and limitations of AI-driven interactivity?

The primary contribution of this work is a comparative analysis that provides empirical evidence on the efficacy of AI-enhanced immersive media in boosting engagement in an architectural heritage context. Furthermore, the study offers concrete insights from a specialist user group that can inform the design of future interactive heritage platforms, moving them from presentation tools towards intelligent pedagogical partners.

The remainder of this paper is structured as follows: Section 2 reviews related work in immersive heritage, AI in cultural heritage, and user experience evaluation. Section 3 details the methodology, including the system architecture and experimental design. Section 4 presents the quantitative and qualitative findings. Section 5 discusses the implications of these findings, outlines design recommendations, and acknowledges the study's limitations. Finally, Section 6 concludes the paper and suggests directions for future research.

2. LITERATURE REVIEW

2.1. The Technological Choice: 360° Media vs. 3D Models in Digital Heritage

A central decision in designing immersive heritage experiences is the selection of the capture technology, a choice primarily between 360° photography and full 3D models. The decision involves a critical trade-off between photorealistic accessibility and high-fidelity interactivity (Wang *et al*. 2024; Moskvin, *et al*. 2025).

360° photography is recognized for its efficiency and ability to deliver a strong, accessible sense of presence. It involves capturing a full spherical view of a location, creating an immersive environment that is particularly effective for visual documentation and virtual tours. Its primary strengths are its cost-effectiveness, rapid deployment, and the photorealistic visual fidelity it provides, making it an excellent tool for capturing the authentic ambiance and materiality of a site. However, a significant limitation is its lack of depth information and geometric data, which restricts user interaction to predefined viewpoints and makes tasks like precise measurement impossible. The experience, while immersive, can remain passive as users are "confined to the camera locations" without the freedom to explore the space freely.

In contrast, 3D scanning and modeling creates a "digital twin" of an object or environment, capturing its exact geometry, shape, and texture. This approach enables a truly interactive experience where users can freely zoom, rotate, and navigate the virtual space, offering unparalleled opportunities for detailed inspection of architectural elements. The downside is the considerable complexity, cost, and need for specialized equipment and expertise, which can be prohibitive. This often limits the use of detailed 3D models to well-funded or mission-critical projects.

For this study, the choice of 360° photography was strategic. It prioritizes accessibility, rapid deployment, and photorealistic visual fidelity, allowing the research to isolate the variable of AI-driven interactivity as the primary intervention. This methodological decision ensures that any measured increase in engagement can be more confidently attributed to the AI guide rather than the novelty or superior interactivity of a 3D environment.

2.2. Immersive Media and Engagement in Educational Contexts

A central decision in designing immersive heritage experiences is the selection of the capture technology, a choice Immersive technologies like Virtual Reality (VR) are increasingly applied in educational settings due to their capacity to enhance user engagement and comprehension. The power of immersive journalism, for instance, lies in its ability to shift audiences from passive consumers to active participants in a story, fostering a deeper connection with the content. Research indicates that VR experiences can produce heightened emotional responses, leading to greater empathy and understanding of complex subjects.

A study on 360° advertising videos found that participants using head-mounted displays rated content as more credible and expressed greater behavioral intentions compared to those using smartphones, demonstrating the significant impact of the immersive modality on user perception. These findings underscore the potential of immersive media to create engaging and impactful experiences, a principle that directly extends to heritage education.

2.3. The Emerging Role of AI and Personalization

The integration of Artificial Intelligence (AI) offers a pathway to overcome the inherent passivity of 360° environments. The concept of personalization is a key strength of AI, with research in other fields, such as e-learning, demonstrating that recommending suitable paths based on user preferences can improve learning outcomes and save time. In journalism, the emergence of the Metaverse highlights a shift towards user-generated content and active participation, demanding new skills for fact verification and audience guidance. For architectural heritage education, an AI guide can act as a personalized mediator, transforming a static visual tour into a dynamic, dialogic learning session. It can provide context-aware information and answer spontaneous, technically specific queries from students, thereby addressing the limitation of pre-scripted, non-interactive content (Alhilal, *et al*. 2024; Fanini, *et al*. 2025).

2.4. Synthesis and Identified Research Gap

In summary, the literature confirms a clear trajectory: while 360° media offers an accessible and realistic method for virtual heritage site capture, it often fosters a passive user experience. Concurrently, AI and immersive technologies have proven potential to boost engagement and enable personalization, yet their integration within a cohesive, web-based heritage education tool for specialized audiences remains underexplored.

This study bridges this gap by investigating the integration of a generative AI tour guide within a WebGL-based 360° environment. It contributes empirical evidence from a controlled experiment with architecture students, a key stakeholder group whose engagement with heritage is inherently analytical. The research quantitatively and qualitatively measures how AI-driven conversation can mitigate the limitations of a passive 360° tour, thereby providing insights that are both technologically grounded and pedagogically relevant.

3. METHODOLOGY

This study employed a controlled, between-subjects experimental design to investigate the impact of a spatially-aware AI-guided WebGL environment on user engagement. A total of 20 undergraduate students from the Department of Architecture, Hong Kong Chu Hai College were recruited for this study. This purposive sampling of architecture students was a deliberate methodological choice. As the research aims to investigate the impact of an AI guide on architectural understanding, it was critical to engage participants who possessed the foundational knowledge to appreciate the domain-specific guidance and provide meaningful feedback on its utility. A homogeneous, expert sample at this stage allows for a more controlled and in-depth analysis of the core interaction mechanism, reducing noise from variability in prior knowledge. While this limits the statistical generalizability to the broader population, it significantly enhances the validity of the findings for the target user group for which such a tool is designed.

3.1. Experimental Platform and Materials

The core of this study was a custom-developed, web-based platform accessible via mobile device browsers to maximize accessibility and replicate a common user scenario. The platform was built using the A-Frame.js framework.

- Virtual Environment & Heritage Site: The immersive environment was constructed using high-resolution 360° panoramic photographs of Murray House, a Victorian-era building in Stanley, Hong Kong. This site was selected for its rich architectural and historical significance.

- Experimental Condition (Spatially-Aware AI Guide): The experimental platform integrated a conversational AI guide powered by the default Deep Seek model via its API. The key innovation was the AI's spatial consciousness. The system continuously tracked the user's virtual position and viewing direction within the 360° environment. This allowed the AI to function as more than a chatbot; it could understand context and provide spatially-relevant guidance. For example, if a user asked, "What is this column style?", the AI would answer based on their current view. Interaction was conducted solely through text-based prompts. The interface of the experimental condition is shown in Figure **1**. Crucially, the AI could also proactively guide users between different locations within the virtual site, as demonstrated in Figure **2**, thereby directing attention to specific architectural features.

Figure 1: Interface of the AI-guided experimental condition. The screenshot shows the 360° view of Murray House with the AI guide (represented as a robot avatar) and its text-based instruction: "Look at the column on your left side. Try to focus on the blue circle to call out more information!"

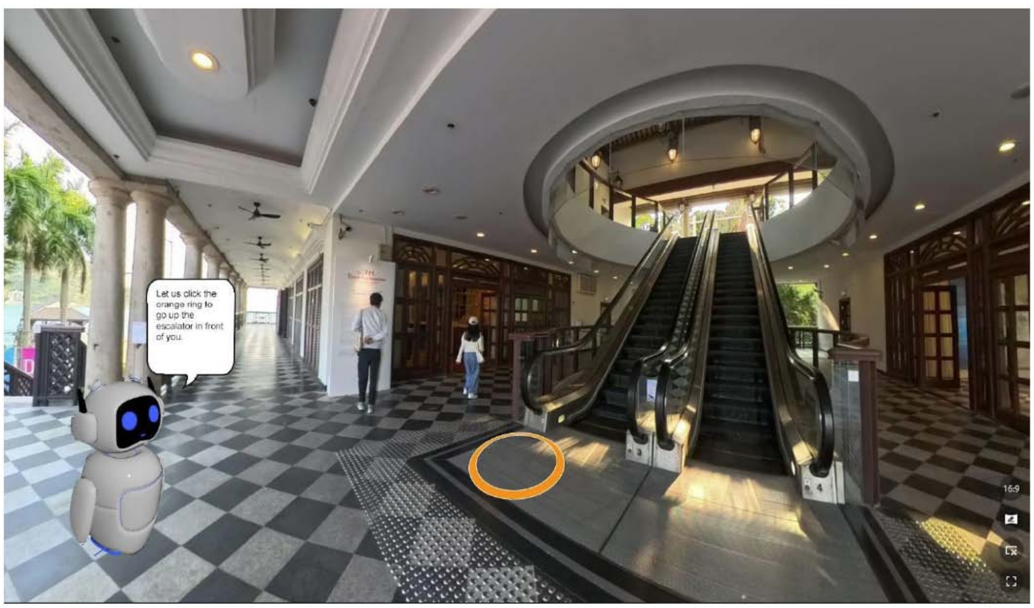

Figure 2: AI-guided navigation between scenes. This screenshot depicts the moment of transition, showing the AI guide prompting the user: "Let us click the orange ring to go up the escalator in front of you".

- Control Condition (Pure 360°): The control platform presented an identical set of interconnected 360° photos of Murray House within the same A-Frame.js environment, but contained no AI guide or additional interactive features.

3.2. Procedure

The experiment was conducted in a controlled lab setting where participants used their own smartphones. Upon arrival, participants were briefed and randomly assigned to a condition. They were given a standardized 5-minute introduction to the navigation controls. Participants in the experimental group received an additional 2-minute demonstration on the text-based AI interface and its capability for spatial guidance.

Each participant was then given 15 minutes to freely explore the virtual heritage site. Following the interaction, they immediately completed a post-experience questionnaire. The entire session lasted approximately 25-30 minutes.

3.3. Data Collection and Measures

A mixed-methods approach was used.

- Quantitative Behavioral Metrics: The platform logged:
- Number of AI Interactions (Experimental group only)
- Navigation Comprehensiveness (Percentage of nodes visited)
- Quantitative Survey Data: A post-test questionnaire used a 5-point Likert scale to measure Perceived Engagement, Perceived Learning, and Satisfaction.
- Qualitative Feedback: Open-ended questions gathered insights on the user experience, with a focus on the utility of the spatially-aware guidance.

4. FINDINGS

This section presents the results of the controlled experiment, analyzing both quantitative and qualitative data to address the research questions. The findings demonstrate a significant positive impact of the spatially-aware AI guide on both behavioral and cognitive engagement with the virtual heritage site.

4.1. Quantitative Behavioral Metrics

Analysis of the automatically logged interaction data revealed substantial differences between the experimental (AI-guided) and control (360°-only) groups.

- Navigation Comprehensiveness: The AI group visited a significantly higher percentage of the available 360° photo nodes (M = 90%, SD = 5%) than the control group (M = 60%, SD = 12%)

4.2. Quantitative Survey Data

Post-experience survey results, measured on a 5-point Likert scale, strongly supported the behavioral data.

- Perceived Engagement: The AI-guided group reported significantly higher levels of focused attention and overall engagement (M = 4.5, SD = 0.5) compared to the control group (M = 3.1, SD = 0.8)
- Perceived Learning: Participants in the experimental group felt they gained a much deeper understanding of Murray House's architecture (M = 4.6, SD = 0.5) than those in the control group (M = 3.3, SD = 0.7)
- Satisfaction: Overall satisfaction was also significantly higher for the AI-guided experience (M = 4.7, SD = 0.4) versus the passive tour (M = 3.4, SD = 0.9)

4.3. Qualitative Feedback

Thematic analysis of the open-ended responses provided rich context for the quantitative findings, highlighting the value of the AI's spatial awareness.

- Theme 1: Guided Discovery and Deepened Inquiry. AI-group participants consistently praised the system for directing their attention to details they would have otherwise missed. One participant noted, "I would have just walked past the brickwork, but the AI pointed out the different bonding patterns and explained their structural reason, which was fascinating." Another stated, "It felt like having an expert architect with me, telling me not just what something is, but why it's important to look at."
- Theme 2: Dynamic and Contextual Dialogue. The ability to ask questions about what was immediately in view was a key differentiator. A student commented, "Instead of just reading a plaque, I could ask 'How was this column fabricated?' and get an immediate, detailed answer. It made the building come alive."
- Theme 3: Passive vs. Active Experience. In stark contrast, feedback from the control group emphasized the experience's limitations. A typical response was, "It was pretty to look at, but I didn't really learn much. I just clicked from one room to the next without any direction or way to ask questions." This underscores the passivity of the traditional 360° tour.

In summary, the integration of a spatially-aware AI guide resulted in statistically significant and qualitatively richer engagement. The AI group not only explored the virtual environment more thoroughly and for a longer duration but also reported a more educational, satisfying, and active learning experience, directly attributable to the context-aware, interactive guidance.

5. DISCUSSION

The findings of this study provide robust evidence that the integration of a spatially-aware AI guide fundamentally transforms the user experience within a web-based, 360° virtual heritage environment. The results fully address the research questions, demonstrating not only a quantitative increase in engagement but a qualitative shift from passive observation to active, dialogic exploration. This section interprets these findings, discusses their implications, acknowledges the study's limitations, and suggests directions for future research.

5.1. Interpretation of Key Findings

The more comprehensive navigation patterns observed in the AI-guided group (RQ1) clearly indicate enhanced behavioral engagement. This is not merely a function of the time taken to type questions; it reflects a deeper investigative process. Users were not just viewing a space—they were interrogating it. Users trusted the AI as a knowledgeable guide and were motivated to follow its lead, leading to a more structured and thorough inspection of Murray House's architectural features.

The survey data and qualitative feedback powerfully address RQ2, revealing the perceived benefits for architectural understanding. The high scores on perceived learning and satisfaction, coupled with comments like "It felt like having an expert architect with me," underscore the AI's role as a cognitive tool. The AI did not just provide information; it scaffolded the learning process by directing attention to salient elements (e.g., brickwork bonding, column fabrication) and providing immediate, context-specific explanations. This directly mitigated the "passivity" problem associated with traditional 360° tours, which was explicitly lamented by the control group. The key differentiator was the AI's spatial consciousness, which enabled a conversational dynamic grounded in the user's immediate perceptual reality, making the interaction intuitive and relevant.

5.2. Theoretical and Practical Implications

Theoretically, this study moves the field beyond a techno-centric view of immersion. It demonstrates that true immersion in a heritage context is not solely a product of visual fidelity but is equally dependent on interactive and intellectual depth. The research provides a model for what can be termed "Dialogic Immersion," where user agency, facilitated by AI, is central to the experience.

Practically, this work offers a scalable and accessible blueprint for heritage institutions and educators. The use of a web-based platform (A-Frame.js) and a commercially available AI API (Deep Seek) means that creating such intelligent, guided tours does not require prohibitive investment in proprietary software or hardware. For architectural education, this tool can augment site visits, provide access to remote or fragile sites, and help students develop critical observation skills by learning what questions to ask and where to look.

5.3. Limitations and Future Work

This study has several limitations that also chart a course for future research. First, the use of the default, untrained Deep Seek model is a recognized constraint. While it performed effectively, its responses were generic at times. A clear next step is to fine-tune the AI model on a specialized corpus of architectural history, conservation principles, and specific data on Murray House to improve accuracy and domain-specific depth.

Second, the platform was accessed via mobile browsers to establish a baseline. A direct and compelling extension of this work is to integrate the same AI-guided system into a smartphone-based VR headset to study the effects of full immersive VR on presence and engagement, and to explore gesture-based and voice-based interactions.

Finally, the participant pool, while appropriate for this initial study, was limited to 20 architectural students from one institution. Future work should expand to include a larger and more diverse sample, including general tourists, history students, and conservation professionals, to compare engagement patterns across different user profiles.

6. CONCLUSION

This research set out to investigate whether an AI tour guide could enhance engagement in a 360° virtual heritage site. The results affirm that it can, and to a significant degree. By developing a WebGL platform that integrated a spatially-aware AI guide for Murray House in Hong Kong and comparing it to a standard

360° tour through a controlled experiment, we found that the AI group exhibited longer, more thorough exploration and reported a more educationally rewarding and satisfying experience.

The major contribution of this work is the demonstration that the synergy of lightweight web technologies and generative AI can create powerful, accessible pedagogical tools. The AI transformed the virtual environment from a passive gallery into an interactive learning space, guiding architectural students to see not just the "what" of a heritage structure, but the "why" and "how." This approach promises a new paradigm for digital heritage—one that is not only about preserving how sites look but also about fostering a deeper, more inquisitive engagement with what they mean. Future work will focus on refining the AI's expertise and testing this model in fully immersive and diverse educational contexts.

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