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Immersive Heritage Trails through Sensory Storytelling for Enhanced Visitor Learning

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Abstract. *Growing demand for meaningful cultural engagement encourages heritage institutions to move beyond passive observation toward immersive visitor learning. This study proposes a conceptual framework for immersive heritage trails that integrates sensory storytelling through coordinated multisensory cues. A narrative literature review synthesized principles of immersive experience design and multisensory interaction to inform a simulated digital heritage trail. The framework aligns narrative structure with visual, auditory, tactile, and olfactory stimuli to support coherent, contextually grounded interpretation. A simulation-based comparison evaluated a conventional interpretive trail and the proposed model against selected design criteria using rule-based evaluators. The proposed model achieved a 100% higher simulated narrative engagement potential score and a 109% higher simulated knowledge retention score than the conventional scenario. These percentages describe relative differences between hypothetical scores, not measured improvements in visitor engagement or learning. The findings illustrate the design potential of integrating sensory cues within a unified heritage narrative but do not establish effectiveness in real-world settings. Because the evaluation involved neither actual visitors nor human experts, its outcomes remain preliminary and assumption-dependent. This study contributes a conceptual design framework and a transparent simulation-based evaluation approach for heritage interpretation and digital placemaking. Future research should assess the framework through human expert reviews and field studies with visitors to establish its practical applicability and effects on learning outcomes across diverse cultural contexts.*

Keywords: *Digital Placemaking, Immersive Heritage Design, Multisensory Interaction, Narrative Engagement, Visitor Cognition*

INTRODUCTION

The integration of digital technologies within the cultural heritage sector has fundamentally transformed the relationship between visitors and artifacts, shifting the paradigm from static observation toward dynamic interaction. Contemporary heritage design increasingly prioritizes engaging visitor experiences that stimulate not only visual appreciation but also cognitive and affective involvement. This evolution aligns with evidence indicating reduced attention spans in conventional museum settings and a growing expectation for personalized and interactive narratives (Bec et al., 2019; Kuhail et al., 2022; Leow & Ch'ng, 2021). In parallel, developments in immersive and experience-oriented design suggest that cultural audiences increasingly seek meaningful encounters that foster knowledge acquisition and long-term memory formation rather than passive information consumption (Echavarria et al., 2022; Pisoni et al., 2021). Consequently, heritage trails and museum exhibitions face increasing pressure to adopt design approaches capable of meeting these evolving experiential expectations.

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The rise of digital immersion has introduced technologies such as virtual reality (VR), augmented reality (AR), and mixed reality (MR) into heritage contexts (Bekele, 2021; Challenor & Minhua, 2019). While these technologies enable the reconstruction of historical environments and visualization of lost artifacts, challenges remain in translating sensory input into meaningful narrative understanding. Many existing applications emphasize visual spectacle and technological novelty while underutilizing other sensory dimensions such as sound, touch, and smell (Guo et al., 2021; Marto et al., 2020). This visual dominance may constrain opportunities for deeper cognitive engagement and interpretive understanding associated with multimodal processing. Furthermore, digital interventions are often insufficiently integrated with the physical environment, resulting in fragmented rather than seamless visitor experiences. Despite technological advancements, current digital heritage implementations remain visually dominant and may benefit from more integrated multimodal narrative frameworks that connect sensory experiences with contextual interpretation.

Previous research has established the effectiveness of individual components of digital heritage experiences. Virtual heritage studies demonstrate that VR environments enhance spatial understanding and presence, improving cultural knowledge acquisition when paired with appropriate interaction design (Bekele & Champion, 2019; Škola et al., 2020). Interactive storytelling approaches have also been explored as a means of conveying intangible cultural heritage by connecting historical narratives with contemporary audiences (Nikolakopoulou et al., 2022; Rizvić et al., 2019). Additionally, gamification and tangible interaction techniques support collaborative and situated learning within heritage environments (Nofal et al., 2020; Pagano et al., 2020). However, these approaches are typically developed in isolation. The integration of place-based heritage trails with coherent, sensory-rich narrative structures remains insufficiently explored. Existing studies rarely address how multiple sensory channels can be systematically orchestrated within a unified interpretive design. This study therefore focuses on the conceptual organization of multisensory storytelling within heritage trails rather than assuming that combining sensory channels automatically produces measurable learning gains.

Recent work in human-centered and participatory design highlights the importance of co-creative storytelling and visitor-centered experiences (Echavarria et al., 2022; Pisoni et al., 2021). Research on multimodal interaction further indicates that combining multiple sensory channels may offer opportunities to support visitor engagement and comprehension (Hammady & Strathearn, 2020; Raptis et al., 2021). Nevertheless, a critical methodological limitation persists. Although field-based evaluation can provide evidence about actual visitor responses, such evaluation may require substantial resources and implementation time. Simulation-based

approaches can offer an initial means of examining design alternatives before field deployment; however, their results cannot substitute for empirical evidence obtained from actual visitors. There is a need for a clearly specified conceptual framework and preliminary simulation-based approach that enable designers to organize and compare alternative heritage trail designs prior to implementation, while recognizing the limitations of simulated evaluation.

Moreover, theoretical perspectives on immersion and flow have largely been applied to digital games and virtual environments, with limited extension to physical heritage trails enhanced by sensory design (Zhang & Gao, 2021). While prior studies confirm that alignment between sensory stimuli and narrative context is essential for meaningful interpretation and visitor satisfaction (Guo et al., 2021; Marto et al., 2020), the systematic application of these principles to extended, place-based heritage experiences warrants further conceptual development. Therefore, a critical problem persists: the absence of an integrated conceptual framework that organizes multisensory storytelling in relation to narrative coherence, sensory congruence, and potential visitor engagement in heritage trail design. This gap highlights the need for a unified framework that integrates experience design, sensory storytelling, and simulation-based assessment criteria without treating simulated scores as direct measurements of actual visitor learning.

Addressing this issue is particularly relevant as cultural institutions seek engaging, educational, and memorable visitor experiences. This study addresses the identified gap by proposing a conceptual framework for immersive heritage trails that uses sensory storytelling to structure interpretive experiences and explore their potential to support visitor learning. The primary objective is to formulate a structured design framework that supports the systematic integration of visual, auditory, tactile, and olfactory cues within a coherent narrative. A secondary objective is to conduct a preliminary, simulation-based comparison between a conventional text-based interpretive trail and a sensory-rich model using selected design criteria. The comparison examines differences in simulated evaluation scores rather than measuring actual changes in visitor engagement, knowledge acquisition, or long-term retention. Using a narrative literature review and scenario-based simulation with representative data, this study illustrates how literature-informed criteria can be applied to compare alternative design scenarios before empirical testing.

The novelty of this research lies in its combined theoretical and methodological contributions. Theoretically, it extends the application of immersion and flow concepts to place-based heritage experiences by linking sensory orchestration with design considerations relevant to narrative coherence and potential cognitive engagement. Methodologically, it introduces a

preliminary simulation-based procedure for comparing design alternatives using literature-informed visitor experience criteria and explicitly defined evaluation dimensions. Because the procedure relies on simulated scenarios and rule-based evaluators rather than human experts or actual visitors, it should be understood as an exploratory assessment approach, not as an empirically validated evaluation method. Practically, the proposed conceptual design framework offers a starting point for heritage practitioners to consider how visual, auditory, tactile, and olfactory cues may be coordinated within interpretive narratives. Its practical effectiveness and its influence on visitor learning outcomes remain to be established through human expert assessment and field studies involving actual visitors.

LITERATURE REVIEW

A. Theoretical Foundations of Experience and Immersion

The conceptual underpinnings of immersive heritage design are firmly rooted in the principles of experience design, which prioritize the creation of memorable and meaningful interactions over the passive delivery of content. Within the context of cultural tourism and museums, management models for immersive heritage experiences emphasize the orchestration of technology, narrative, and environment to facilitate a state of deep visitor engagement (Bec et al., 2019). This perspective aligns with the foundational elements of flow theory, which posits that optimal experiences arise from a delicate balance between perceived challenge and individual skill, leading to a state of total absorption in the activity at hand (Zhang & Gao, 2021). When applied to heritage trails, the flow state is contingent upon the design's ability to maintain visitor focus, provide clear narrative goals, and deliver immediate sensory feedback that reinforces the learning journey. However, existing implementations often fail to operationalize these theoretical principles into coherent design strategies, resulting in experiences that are technologically rich but cognitively fragmented. The absence of such deliberate design can lead to cognitive discontinuity, where the visitor’s attention oscillates between the digital interface and the physical environment without achieving a unified understanding of the heritage narrative.

B. Technological Vectors and Sensory Engagement

A significant body of empirical work has investigated the technological vectors for achieving immersion in heritage contexts, with particular emphasis on extended reality (XR) applications. Comparative studies of immersive realities reveal that the method of interaction whether through gesture, gaze, or controller significantly influences the efficacy of cultural learning (Bekele & Champion, 2019). While virtual reality systems incorporating 360-degree video storytelling enhance presence and narrative immersion, they often isolate users from the

multisensory affordances of the physical heritage environment (Argyriou et al., 2020; Škola et al., 2020), whereas augmented reality enables contextual integration by overlaying digital content onto real-world settings (Challenor & Minhua, 2019). This distinction highlights a fundamental trade-off between immersion depth and environmental continuity. Research examining multisensory stimuli in AR applications further demonstrates that congruent sound, haptic feedback, and scent significantly enhance user presence, enjoyment, and perceived knowledge value (Marto et al., 2020). However, many of these studies remain technologically driven, prioritizing system performance and sensory novelty over narrative coherence and cognitive integration. This evidence suggests that the future of heritage trail design lies not in a singular technological solution, but in a curated ecosystem of sensory cues that are meaningfully aligned with narrative intent.

C. Narrative as Cognitive Scaffold

Storytelling functions as the cognitive scaffold upon which multisensory information is organized and rendered meaningful within the visitor's mind. In heritage contexts, storytelling facilitates a co-creative process in which visitors actively construct meaning from narrative and sensory inputs (Echavarria et al., 2022). The design of audience-centric experiences requires an understanding of narrative transportation, a psychological mechanism through which individuals become absorbed in a story (Leow & Ch'ng, 2021). When immersive storytelling is effectively implemented, cognitive resources are directed toward the narrative world, reducing counterarguing and enhancing knowledge construction. Studies on embodied interaction further demonstrate that physical engagement such as manipulating tangible artifacts anchors abstract historical concepts in concrete sensory experience (Chu & Mazalek, 2019). In contrast, poorly integrated sensory elements may function as distractions rather than facilitators of meaning-making, weakening narrative coherence and interpretive depth. Consequently, sensory storytelling must be designed with precision, ensuring that each sensory modality contributes directly to narrative progression rather than serving as superficial augmentation.

D. Participatory and Human-Centered Methodologies

The integration of participatory and co-design methodologies represents a significant shift toward human-centered practice in digital heritage development. Research highlights the importance of involving end-users, including local communities and visitors, to ensure cultural authenticity and interpretive relevance (Okanović et al., 2022; Pisoni et al., 2021). By employing iterative design processes, heritage experiences can be tailored to diverse cognitive preferences and learning styles. This participatory approach is particularly critical in the representation of intangible cultural heritage, where meaning is embedded in practice, performance, and oral

tradition (Tzima et al., 2020). Projects utilizing interactive storytelling and projection mapping demonstrate that co-created narratives can enhance both cognitive and affective engagement (Nikolakopoulou et al., 2022). However, while participatory approaches improve contextual relevance, they often lack structured mechanisms for integrating multisensory design decisions into a coherent evaluative framework. This limitation reduces their scalability and consistency across different heritage contexts. The implication for this study is that sensory storytelling frameworks must balance flexibility with systematic design principles.

E. Cognitive Justification and Identified Gap

The cognitive mechanisms underlying multisensory learning provide a strong theoretical foundation for this research. The human brain encodes and retains information more effectively when multiple sensory modalities are engaged simultaneously, strengthening memory structures and retrieval pathways (Wang, 2020). When visual, auditory, and tactile inputs are congruently aligned, both comprehension and retention are significantly enhanced. Empirical studies in digital museum contexts confirm that multisensory cues improve visitor engagement and perceived knowledge value, particularly when sensory elements are congruent with the narrative context (Brengman et al., 2022; Guo et al., 2021). These findings support the premise that integrated sensory storytelling can enhance interpretive understanding and experiential depth.

However, despite this strong theoretical and empirical foundation, existing research remains fragmented across technological, narrative, and cognitive domains. While prior studies have evaluated usability and mental workload in AR storytelling applications (De Paolis et al., 2022), they fail to provide a generalizable and simulation-ready methodology for assessing the pedagogical implications of different sensory design strategies prior to real-world implementation. The literature demonstrates the effectiveness of individual components XR technologies, storytelling techniques, and multisensory interaction but lacks a unified, replicable framework capable of integrating these elements into a coherent design and evaluation model. This fragmentation represents a critical limitation in advancing immersive heritage design from experimental applications to scalable and systematic practice. The present study addresses this gap by synthesizing immersion theory, sensory engagement, and narrative structuring into an integrated framework, supported by a comparative simulation approach that bridges conceptual design and empirical evaluation.

METHODS

A. Research Design

This study employed a two-phase methodological approach consisting of a narrative literature review followed by a comparative design simulation. The primary objective was to develop a proposed conceptual design framework for immersive sensory storytelling on heritage trails and explore its application through a simulation-based comparison, rather than empirically validate its effectiveness. The research design was structured to synthesize relevant principles from the existing academic literature and apply them within a scenario-based comparison of alternative heritage trail designs.

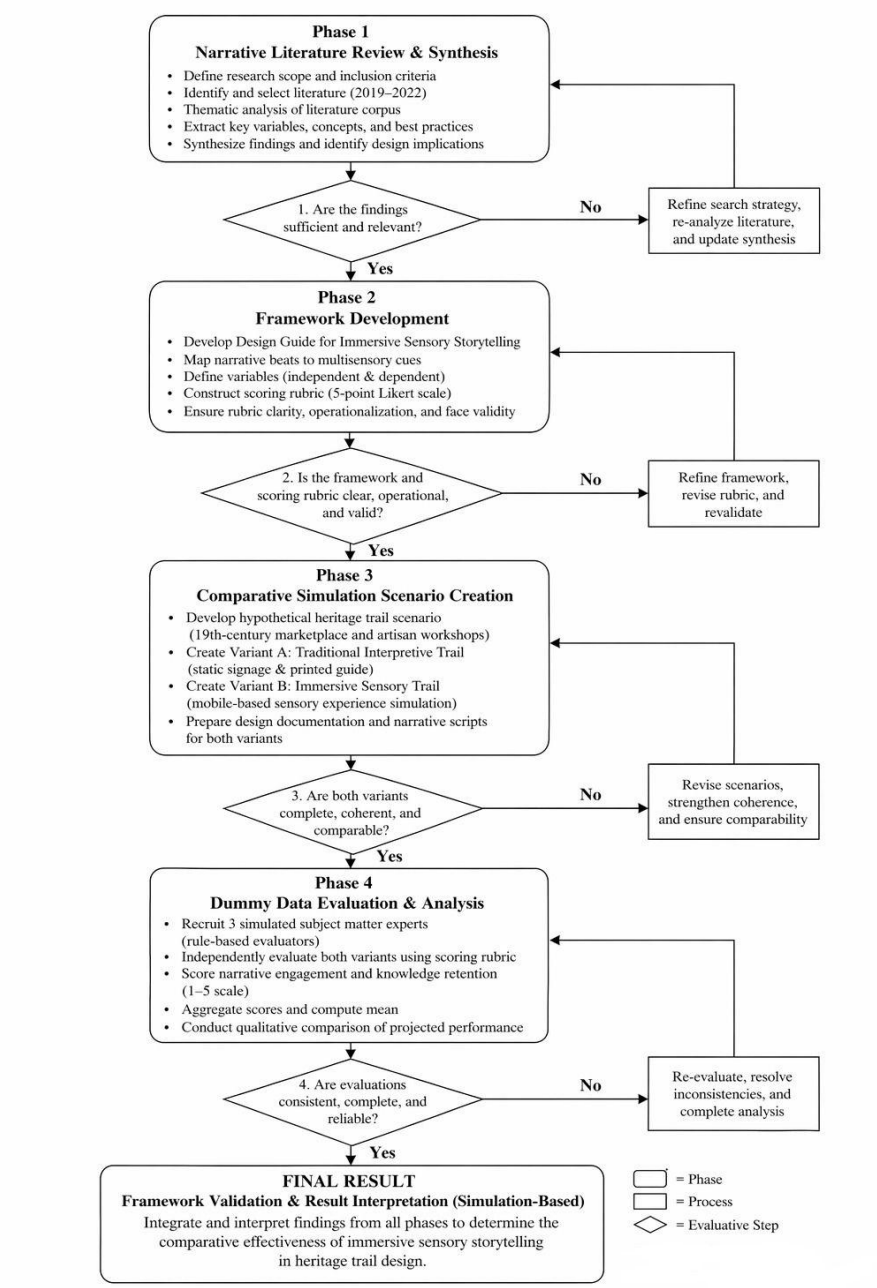


Figure 1. Research Flow of the Immersive Heritage Trail Design Study

This approach was selected to support the preliminary examination of design alternatives before physical implementation. The simulation was intended to illustrate how literature-informed criteria could be applied to compare two design scenarios; it was not designed to establish actual improvements in visitor engagement, knowledge acquisition, or retention. The research was conducted in a simulated digital environment using constructed scenarios rather than observations or experimental data collected from actual visitors. Accordingly, the findings are exploratory and do not constitute empirical validation of the proposed framework or validation by human experts. The overall research flow is illustrated in Figure 1.

B. Population and Sample

The narrative literature review served as the foundational phase, targeting a purposive sample of peer-reviewed literature published between 2019 and 2022. The literature of interest comprised scholarly articles, conference proceedings, and academic book chapters addressing the intersection of cultural heritage, immersive technologies, and multisensory experience design. The literature considered in this study was drawn from the sources included in the study's reference framework; therefore, the review should be understood as a narrative synthesis rather than an exhaustive systematic review. Inclusion criteria stipulated that sources discuss one or more of the following thematic areas: immersive heritage or virtual tourism design frameworks, applications of multisensory or tangible interaction in cultural contexts, the role of storytelling in visitor engagement, or evaluations of visitor learning outcomes in informal educational settings. Sources focusing solely on technical implementation without a pedagogical or experiential component were excluded from the synthesis. The literature informed the conceptual framework and the selection of evaluation criteria; it did not serve as direct evidence that the simulated trail designs would produce specific learning outcomes among actual visitors.

C. Data Sources and Collection Techniques

The data collection process involved a thematic synthesis of the selected literature. This process drew on qualitative synthesis approaches used in human-centered design and cultural heritage studies (Hammady & Strathearn, 2020; Pisoni et al., 2021). Each source was examined to identify design principles relevant to the proposed framework, particularly the relationship between narrative structure, sensory cues, and visitor experience. The resulting criteria were literature-informed conceptual criteria rather than independently validated measures of visitor learning.

The independent design characteristics concerned the presence and contextual congruence of multisensory cues within a cohesive narrative. These cues included visual stimuli, auditory stimuli, tactile stimuli, and olfactory stimuli. The comparison focused

on four evaluation dimensions: narrative engagement potential, knowledge-retention potential, narrative coherence, and sensory congruence. These dimensions were used to describe and compare the simulated design scenarios; they were not treated as direct measurements of actual visitor responses. The literature synthesis provided the conceptual basis for defining these dimensions and applying them to the two trail variants.

D. Variables and Operational Definitions

The independent design characteristics in this simulation were defined as the presence and contextual congruence of multisensory cues integrated within a cohesive narrative structure. These cues were categorized into four distinct modalities: visual stimuli (simulated AR overlays and environmental graphics), auditory stimuli (geolocated ambient soundscapes and narrative voice-overs), tactile stimuli (haptic feedback patterns synchronized with narrative events), and olfactory stimuli (simulated scent cues at designated trail nodes). These modalities were represented as features of the constructed design scenarios and were not physically delivered or tested with actual visitors.

The evaluation dimensions focused on the potential of each design variant to support visitor engagement and learning, rather than on measured visitor outcomes. Narrative engagement potential was defined as the extent to which the narrative structure and proposed sensory cues were designed to encourage emotional involvement, focused attention, and immersion in the story. Because no actual visitors participated in the simulation, this dimension did not measure visitors' experienced narrative transportation or engagement. Knowledge-retention potential was defined as the extent to which historical facts, contextual relationships, and cultural meanings were organized within the scenario to support potential recall after the interpretive experience. No visitor recall test was conducted; therefore, this dimension represented projected learning potential rather than measured knowledge retention.

Two additional dimensions were used to compare the design variants. Narrative coherence referred to the logical consistency between the historical narrative, the sequence of interpretive content, and the events or locations represented in the trail. Sensory congruence referred to the degree of contextual alignment between the narrative content and the proposed visual, auditory, tactile, and olfactory cues. These dimensions were intended to assess the conceptual relationship between narrative structure and

sensory design, not to establish the independently verified effectiveness of any sensory modality.

All four dimensions were assessed using a five-point scoring scale, ranging from 1 (very low alignment with the stated criterion) to 5 (very high alignment with the stated criterion). Scores were assigned by applying the same dimension definitions to the descriptions and narrative scripts of Variant A and Variant B. The criteria were informed by a synthesis of relevant literature on immersive experiences, multisensory interaction, and visitor learning (Brengman et al., 2022; Guo et al., 2021). The scale served as a descriptive tool for the simulation and was not a psychometrically validated instrument. Accordingly, the resulting scores indicate relative alignment with the study's literature-informed conceptual criteria, rather than empirically measured visitor responses or learning outcomes.

E. Measurement Instruments and Validity

Based on the thematic analysis of the literature, a structured conceptual design framework for immersive sensory storytelling was developed to organize the relationship between narrative elements and proposed sensory cues. The framework served as a design and comparison aid rather than a validated measurement instrument. It was applied to construct a simulated heritage trail scenario set in a hypothetical urban historical district featuring a nineteenth-century marketplace and adjacent artisan workshops.

Two design variants were constructed for comparison. Variant A represented a Traditional Interpretive Trail that relied on static textual signage and a printed map guide containing historical information. Variant B represented the proposed Immersive Sensory Trail, designed to integrate narrative content with multiple sensory cues. The simulated mobile application for Variant B included geolocated interpretive content, period-appropriate ambient soundscapes, haptic feedback synchronized with descriptions of machinery, and contextual scent cues representing elements such as spices and wood smoke. These features were represented in the scenario documentation; their effects were not tested through physical implementation or visitor interaction.

The scoring rubric operationalized the four evaluation dimensions defined in Section D using the same five-point scale for both variants. A score of 1 indicated very low alignment with a criterion, 2 low alignment, 3 moderate alignment, 4 high alignment, and 5 very high alignment. For narrative engagement potential, the assessment considered whether the scenario incorporated narrative continuity and design features intended to support attention and involvement. For knowledge-retention potential, it considered the

organization and contextual explanation of historical information. For narrative coherence, it considered the logical connection between narrative content, sequence, and trail locations. For sensory congruence, it considered the contextual relationship between each proposed sensory cue and the narrative event it accompanied. These descriptors were intended to make the scoring basis more explicit and consistent across the two scenarios.

The criteria were derived from the same literature synthesis that informed the proposed multisensory framework. Consequently, the assessment was not independent of the framework's theoretical assumptions and may favor design features emphasized by the literature, particularly multisensory integration. This potential circularity was recognized as a limitation. The rubric was therefore used for exploratory scenario comparison, not as evidence that the framework or the rubric had been empirically validated. No formal psychometric validation or independent validation by human experts was conducted in this study.

F. Data Analysis Techniques

Data analysis involved a descriptive comparison of Variant A and Variant B using the literature-informed scoring rubric described in Sections D and E. Three simulated evaluator profiles were used to represent rule-based assessment perspectives informed by the study's selected design criteria. These profiles were computational or conceptual evaluator constructs, not actual subject matter experts, recruited participants, or individuals who independently reviewed the scenarios. Their labels should not be interpreted as evidence of professional qualifications or human expert judgment.

Each simulated evaluator applied the same four evaluation dimensions and five-point scoring scale to the design documentation and narrative scripts for both variants. The scoring logic was based on the stated operational definitions: the evaluator assigned a higher score when the scenario documentation showed stronger alignment with the relevant criterion and a lower score when that alignment was weaker. The same criteria and scale were applied to both variants to maintain consistency within the simulation. The resulting scores were summarized descriptively to compare the scenarios' narrative engagement potential, knowledge-retention potential, narrative coherence, and sensory congruence.

For each evaluation dimension, the mean score was calculated by summing the scores assigned by the three simulated evaluators and dividing the total by three. Where

percentage differences were reported, the relative difference was calculated by subtracting Variant A's mean score from Variant B's mean score, dividing the result by Variant A's mean score, and multiplying by 100. These percentages describe differences between simulated scores only; they do not represent percentage increases in actual visitor engagement or learning. No inferential statistical tests were conducted because the scores were generated through a simulated, rule-based procedure rather than collected from a sample of human participants.

The comparison was exploratory and descriptive. Because the criteria were derived from the literature that also informed the proposed framework, the evaluation cannot establish the framework's superiority through independent testing. The results should instead be interpreted as an illustration of how the selected criteria distinguish two constructed design scenarios. The rule-based evaluators do not reproduce the full variability of human expert judgment, visitor responses, or contextual influences. The approach therefore requires subsequent assessment by human experts and empirical field studies involving actual visitors before conclusions can be drawn about practical effectiveness or learning outcomes.

G. Ethical Considerations

Ethical considerations for this study were addressed through use of published literature, constructed design scenarios, and simulated evaluator profiles. The research did not involve human participants, primary data collection from visitors, or direct interaction with a living heritage community. The simulated evaluator profiles were not real individuals, and the scores were not presented as data collected from human experts. The research materials consisted of generic scenarios and design artifacts rather than observations of actual visitor behavior. The study's conclusions are consequently limited to the literature synthesis and the descriptive comparison of simulated scenarios. They should not be generalized to actual visitors or heritage settings without further empirical evaluation.

RESULTS

A. Comparative Performance of Design Variants

The comparative analysis of the two simulated heritage trail variants revealed differences in their projected performance across four evaluation dimensions: narrative engagement potential, knowledge-retention potential, narrative coherence, and sensory congruence. These results were generated through a literature-informed, rule-based scoring procedure and should be interpreted

as descriptive outputs of a conceptual simulation, rather than empirical evidence of visitor experience or learning. Application of the scoring rubric to Variant A, the Traditional Interpretive Trail, resulted in relatively low to moderate scores. The mean score for narrative engagement potential was 2.3 on a five-point scale, while the knowledge-retention potential score was 2.1. These scores indicate that, according to the study's predefined conceptual criteria, Variant A was judged to offer relatively limited potential for narrative engagement and support for recall. They do not represent observed visitor engagement, measured narrative transportation, or results from an actual knowledge-retention test.

The relatively low scores were associated with the scenario's reliance on text-based interpretation and limited integration of sensory cues. This interpretation is consistent with literature discussing the potential limitations of predominantly text-based interpretation and the possible role of interactive and multimodal approaches in heritage experiences (Rizvić et al., 2019; Tzima et al., 2020). However, the present simulation did not independently test these relationships. The cited literature provides the conceptual background for interpreting the scores, rather than direct confirmation that Variant A would produce lower engagement or weaker memory outcomes among actual visitors.

B. Analysis of Immersive Sensory Trail Outcomes

In contrast, Variant B, the Immersive Sensory Trail designed using the proposed framework, received higher simulated scores than Variant A across the evaluation dimensions. These results were generated through a literature-informed, rule-based evaluation and should be interpreted as descriptive comparisons between two constructed design scenarios, rather than empirical evidence of visitor outcomes. The rule-based simulated evaluation assigned Variant B a narrative engagement potential score of 4.6 on a five-point scale. This score suggests that the scenario aligned strongly with the study's predefined conceptual criteria for encouraging focused attention, emotional involvement, and immersion in the narrative. However, it does not demonstrate that actual visitors experienced immersive or flow-like states. This interpretation is informed by research discussing immersive and interactive environments, multisensory stimulation, and narrative integration (Bekele & Champion, 2019; Škola et al., 2020). Nevertheless, the present simulation did not independently test these relationships or establish that multisensory design produces greater visitor engagement.

The evaluation also indicated that the proposed combination of geolocated auditory cues and haptic feedback was consistent with the framework's intention to connect sensory elements with narrative events. Previous studies have discussed the potential of multimodal interactions to support presence and experiential realism in heritage contexts (Bekele, 2021; Marto et al., 2020). However, the individual contribution of each sensory modality was not independently assessed

in this study. The simulated knowledge-retention potential score for Variant B reached 4.4, compared with 2.1 for Variant A. This difference represents a higher score against the study's conceptual criteria for organizing historical facts, contextual relationships, and cultural meanings to support potential recall. It does not represent a measured improvement in visitor knowledge retention or memory performance, because no actual visitors or recall tests were involved. Although previous research has explored multimodal learning in digital heritage environments (Brengman et al., 2022; Guo et al., 2021), the current findings should be interpreted as exploratory outputs of a conceptual simulation, not as confirmation that the proposed framework improves visitor learning. Furthermore, because the evaluation criteria were informed by literature that discusses the potential benefits of multisensory engagement, the comparison may favor design features consistent with those assumptions. Independent assessment by human experts and field studies involving actual visitors are therefore needed to examine the framework's applicability and determine whether the projected differences correspond to real-world engagement and learning outcomes.

C. Detailed Metrics and Projected Improvements

A more granular analysis of the sensory components within Variant B illustrated how the proposed design scenario aligned with the study's conceptual evaluation criteria. The comparison was based on the documented characteristics of each scenario and did not independently measure the contribution of individual sensory modalities to visitor outcomes. Visual cues functioned as the foundational layer, supplemented by proposed auditory elements such as ambient market sounds and mechanical activity. This design approach is consistent with research discussing the potential role of multimodal interaction in contextual understanding and user engagement in cultural heritage applications (Hammady & Strathearn, 2020; Raptis et al., 2021).

In addition, olfactory cues, such as the proposed scent of spices at marketplace locations, were included to strengthen the contextual relationship between sensory elements and the narrative. However, because no actual visitors participated and no recall tests were administered, the simulation cannot establish that these cues increased the vividness of mental imagery or improved recall of narrative details. Previous studies have discussed the potential relationship between sensory congruence, perceived experience quality, and cognitive engagement (Brengman et al., 2022; Marto et al., 2020). In the present study, these publications informed the conceptual criteria rather than serving as direct evidence that the simulated design produced such effects. Therefore, the comparison illustrates the application of the proposed framework but does not demonstrate that each sensory modality contributes independently or that their integration improves visitor learning.

Table 1. Comparative Evaluation of Heritage Trail Design Variants

Evaluation Metric	Variant A (Traditional Trail)	Variant B (Immersive Sensory Trail)	Projected Improvement
Narrative Engagement Potential	2.3	4.6	+100%
Knowledge Retention Potential	2.1	4.4	+109.5%
Coherence of Narrative Structure	3.0	4.8	+60%
Congruence of Sensory Stimuli	1.5	4.7	+213.3%

The scores represent outputs of a literature-informed, rule-based simulation using a five-point scale. Relative differences were calculated using the formula: (Variant B score − Variant A score) / Variant A score × 100. Percentages are rounded to one decimal place where applicable. These values represent differences between simulated scores, not measured improvements in visitor engagement, knowledge retention, or learning effectiveness.

As shown in Table 1, the largest relative difference in simulated scores was observed for sensory congruence, which increased from 1.5 in Variant A to 4.7 in Variant B. Narrative coherence also received a higher score in Variant B (4.8) than in Variant A (3.0). Within the framework's literature-informed criteria, these differences indicate that Variant B was more closely aligned with the intended integration of sensory cues and narrative structure. However, they do not establish that stronger sensory congruence caused higher engagement or knowledge retention. Because the evaluation criteria were informed by literature that already discusses the potential benefits of multisensory engagement, the scoring process may favor design characteristics consistent with those assumptions. This potential circularity should be considered when interpreting the comparison.

Overall, the results provide an illustrative comparison of two constructed heritage trail scenarios under a common set of conceptual criteria. They do not constitute empirical validation of the proposed framework or evidence of improved visitor engagement and knowledge acquisition. Independent evaluation by human experts and field studies involving actual visitors are needed to assess the appropriateness of the criteria, examine potential evaluator bias, and determine whether the projected differences correspond to real-world visitor experiences and learning outcomes.

DISCUSSION

A. Comparison with Previous Studies

The findings of this comparative simulation reveal differences in the projected design potential of traditional and sensory-immersive heritage trail designs. These results can be discussed in relation to prior research on immersive heritage experiences, but they should not be interpreted as empirical evidence that the immersive variant produces better visitor outcomes. The higher simulated score for narrative engagement potential in the immersive variant is conceptually

consistent with studies examining immersive technologies, including 360-degree storytelling and interactive environments, in relation to user presence and narrative absorption (Argyriou et al., 2020; Škola et al., 2020). Similarly, previous comparative studies have discussed the potential of interactivity and sensory richness to support engagement and cultural understanding (Bekele & Champion, 2019). The present study does not independently replicate or verify these findings. Instead, it applies concepts from this literature to compare two constructed heritage trail scenarios.

While previous research has often examined fully virtual environments, the proposed framework considers how multisensory cues might be integrated into physical heritage settings. This represents a conceptual design proposition rather than evidence that comparable levels of engagement can be achieved in real-world heritage settings. Research on place-based and hybrid immersive experiences provides a relevant theoretical context for this proposition (Bekele, 2021; Challenor & Minhua, 2019). The potential contribution of the present framework is therefore its emphasis on experience-centered design, in which sensory cues are connected to place, narrative progression, and historical context, rather than on the adoption of immersive technology alone.

The higher simulated score for knowledge-retention potential in Variant B also requires cautious interpretation. Previous studies in augmented and mixed reality contexts have explored how congruent sensory inputs, including sound, touch, and scent, may relate to perceived learning and cognitive processing (Guo et al., 2021; Marto et al., 2020). Although this literature informs the rationale for the proposed framework, the present simulation did not measure actual learning, memory performance, or recall among visitors. Consequently, the score comparison cannot confirm that multisensory integration improves knowledge retention in heritage settings. A key conceptual proposition of this study is that multisensory design should consider not only the presence of multiple stimuli but also their coherence and alignment with the narrative structure. Previous research has discussed the relevance of sensory alignment to perception and memory in immersive environments (Brengman et al., 2022). In the present study, sensory congruence functions as a literature-informed design criterion, not as an empirically established causal factor influencing engagement or retention. This positions the proposed framework as a conceptual contribution linking technology-enabled immersion with structured experience design in heritage contexts.

B. Theoretical and Practical Implications

The theoretical implications of this study lie in proposing a conceptual application of flow theory and immersion theory to the design of place-based heritage experiences. While prior research has largely applied these concepts to digital games and virtual environments, the present study explores how these theoretical perspectives can inform the organization of sensory and narrative design elements in physical heritage settings (Leow & Ch'ng, 2021; Zhang & Gao,

2021). The integration of geolocated sensory cues is proposed as a design approach for connecting sensory information with narrative progression and the spatial context of a heritage trail. However, the present simulation does not demonstrate that this integration produces sustained attention, immersion, or improved learning among actual visitors. From a cognitive perspective, the framework conceptualizes immersive sensory design as a potential form of external support for meaning-making and memory formation. This proposition aligns with research on embodied interaction and narrative engagement, which emphasizes the potential role of physical and sensory interaction in cognitive processing (Chu & Mazalek, 2019; Raptis et al., 2021).

From a practical standpoint, the proposed framework offers preliminary design considerations for heritage practitioners and experience designers, rather than a validated or empirically proven design method. It suggests that multisensory heritage experiences can be planned systematically rather than through the addition of technology without a clear interpretive purpose. Specifically, designers may consider (1) identifying key narrative moments that could be supported by relevant sensory cues; (2) developing spatially aligned sensory mappings that correspond to visitor movement along the trail; and (3) ensuring contextual congruence between proposed sensory stimuli, historical narratives, and the heritage environment. These considerations are consistent with human-centered and participatory design approaches that emphasize contextual relevance and user experience in cultural heritage applications (Echavarria et al., 2022; Pisoni et al., 2021). The framework's practical applicability, however, has not yet been established through independent human-expert evaluation or field testing with actual visitors. Future research should assess its feasibility and usability and investigate whether the proposed integration of visual, auditory, tactile, and olfactory cues is associated with measurable differences in visitor engagement and learning.

C. Limitations

Despite the analytical value of these findings, several limitations must be acknowledged. The most significant limitation lies in the reliance on a conceptual, simulation-based comparative framework using dummy data and rule-based evaluator profiles rather than evaluations conducted by actual human experts or studies involving real visitors. While this approach enables structured comparison of design alternatives against predefined criteria, it does not fully capture the complexity of real-world visitor behavior, including individual differences in perception, prior knowledge, motivation, and sensory responses. As such, the findings should be interpreted as preliminary indications of alignment with the proposed design criteria, not as empirical evidence of improved visitor engagement or learning outcomes. The relative differences reported for narrative engagement potential and knowledge-retention potential represent differences between

simulated scores only, rather than measured increases in actual visitor engagement or knowledge retention.

A further limitation concerns the evaluation criteria and scoring rubric. These were informed by a synthesis of relevant literature and operationalized for conceptual comparison, but they have not been independently validated by human experts or tested for measurement reliability. Although the criteria provide a structured basis for comparing the two design variants, they also introduce a potential circularity risk because the evaluation framework emphasizes multisensory engagement and narrative coherence. Consequently, a design incorporating these characteristics may receive higher scores partly because it aligns with the assumptions embedded in the criteria. The simulated comparison therefore does not independently establish the superiority or effectiveness of multisensory heritage design.

Furthermore, the operationalization of learning-related outcomes in this study was limited to narrative engagement potential and knowledge-retention potential as simulated evaluation dimensions. Although these dimensions are relevant to heritage interpretation, they do not encompass the full spectrum of visitor experience, such as emotional resonance, social interaction, accessibility, and long-term behavioral impact. Moreover, knowledge-retention potential was not measured through visitor recall tests or other direct assessments of learning. The proposed visual, auditory, tactile, and olfactory cues were design components in the conceptual scenarios and were not tested with visitors in a real heritage environment.

Future research should first involve independent human-expert review of the framework, its indicators, and its scoring descriptors, followed by field studies with actual visitors. Such studies should assess the feasibility and contextual appropriateness of the proposed sensory elements and examine their relationships with measurable visitor outcomes, including engagement, interpretation, and knowledge retention. Further investigation should also consider emotional responses, social interaction, accessibility, and longer-term effects to provide a more comprehensive evaluation of immersive heritage design. Until such evaluations are conducted, the proposed framework should be regarded as a conceptual design framework for structuring and comparing design alternatives, rather than a validated method for improving visitor learning.

CONCLUSION

This study proposes a conceptual design framework for immersive heritage trails that integrates sensory storytelling to support the design of visitor learning experiences. By bringing together immersion theory, multisensory cognition, and narrative structuring within a simulation-based evaluation approach, the study illustrates how alternative heritage trail designs can be compared against predefined, literature-informed criteria. The simulated results show higher scores for Variant B than Variant A in narrative engagement potential and knowledge-retention

potential, as well as narrative coherence and sensory congruence. However, these differences represent comparisons between simulated scores and do not demonstrate actual improvements in visitor engagement, knowledge acquisition, or retention. The contributions of this study are threefold. Theoretically, it proposes an application of flow and immersion concepts to place-based heritage experiences. Methodologically, it introduces a simulation-based approach for the preliminary comparison of design alternatives, rather than an empirically validated evaluation method. Practically, it provides a proposed conceptual design framework to help organize visual, auditory, tactile, and olfactory cues in relation to narrative context and spatial progression. The framework emphasizes the potential importance of aligning multisensory elements with narrative meaning and the heritage setting, but the present study does not establish that this alignment improves visitor learning.

Several limitations must be considered when interpreting these contributions. The study relies on hypothetical design scenarios, dummy data, and rule-based evaluator profiles; it does not involve actual visitors or evaluations conducted by human experts. The evaluation criteria are literature-informed and have not been independently validated. Consequently, the findings should be treated as preliminary simulation outputs rather than empirical evidence of the framework's effectiveness. Future research should begin with independent human-expert review of the framework, its indicators, and its scoring criteria, followed by field-based studies involving real visitors. Such studies should assess the feasibility and applicability of the proposed framework and examine its relationship with visitor engagement, interpretation, and knowledge retention. Additionally, further investigation is needed to evaluate the framework's adaptability across diverse heritage contexts and to determine whether the patterns observed in the simulation correspond to outcomes in real-world settings.

AI Contribution Statement

The authors confirm that AI tools were used exclusively for limited editorial support, including grammar correction and clarity enhancement. All substantive aspects of the research such as study design, data analysis, interpretation, and conclusions were conducted independently by the authors, who assume full responsibility for the originality and integrity of the manuscript.

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