DIGITAL HERITAGE (2025)
S. Campana, D. Ferdani, H. Graf, G. Guidi, Z. Hegarty, S. Pescarin, and F. Remondino (Editors)

Designing Personalized Cultural Heritage Serious Games through Gamification, AI and Augmented Reality

F. Martusciello[1 †] A. Bucchiarone[2] and H. Muccini[1]

[1]FrAmeLab, University of L'Aquila, L'Aquila, Italy
[2]SWEN, University of L'Aquila, L'Aquila, Italy

Abstract

Digital technologies are transforming how cultural heritage is accessed, experienced, and preserved, but many applications remain static, lacking personalization and adaptivity. This paper introduces a modular reference architecture that underpins a serious game–based platform integrating Artificial Intelligence (AI), Augmented Reality (AR), and gamification to support personalized learning journeys in cultural heritage contexts. The system integrates adaptive learning pathways, meaningful gamification, and augmented reality to support user-centric engagement. AI-driven recommendations personalize the path of each visitor through path-based learning activities, adapting to individual behavior, preferences, and cognitive profiles. A conversational AI assistant and spatial AR overlays enhance narrative immersion and support situated learning. The architecture enables curators to create flexible, pedagogically informed content through an intuitive visual design interface. A preliminary prototype demonstrates the technical feasibility of the system and how the integration of AI, gamification, and augmented reality can support the development of inclusive, engaging, and educational cultural experiences for diverse audiences.

CCS Concepts
• ***Human-centered computing*** → *Human computer interaction (HCI); Interaction design;* • ***Computing methodologies*** → *Artificial intelligence;* • ***Applied Computing*** → *Education;* • ***Applied computing*** → *Arts and humanities;*

1 Introduction

In recent years, the intersection of Serious Games (SGs) and Cultural Heritage (CH) has opened new horizons to engage, educate, and empower diverse audiences [BG20, MCB*14]. As cultural institutions they seek to make their collections more accessible, interactive and relevant to younger generations of tech-savvy people, transform passive visitors into active participants by deepening engagement and learning [XRBM14, NBB*20]. Engagement can be broadly defined as the quality of the user experience characterized by the depth of investment of a user when interacting with a digital system [CBJK21], therefore, it can be measured in the interest of users in performing activities to achieve specific goals while preserving their motivation and desire to repeat the activity [SF11].

SGs are particularly well suited to support this type of high-engagement learning. By blending the entertainment value of traditional games with purposeful objectives—such as education, skill development, or awareness-raising—SGs provide a compelling format to mediate knowledge in informal settings [HA11]. These game-based systems leverage motivational mechanics such as points, progression, challenge, and feedback to promote sustained attention, self-paced discovery, and storytelling experiences rooted in cultural identity.

The convergence of Artificial Intelligence (AI) and Augmented Reality (AR) with gamification is now enabling a new generation of CH applications [BG20]. AI, especially through generative and adaptive models, enables dynamic creation and real-time personalization of narratives, content, and user experiences [BPSP21]. AR, on the other hand, overlays digital reconstructions and contextual data onto physical spaces, creating immersive, location-aware interactions that blur the boundary between physical and virtual heritage.

Despite these promising advances, many digital CH applications remain limited by static content, fragmented user experiences, and a lack of adaptability to individual preferences [CCG*24a, LIR24]. To address these limitations, we introduce a modular platform built on a reference architecture that integrates gamification, adaptive learning pathways, AI-driven personalization, and AR-enhanced storytelling. This architecture forms the foundation for an interactive platform where each visitor's journey is structured as a path-based learning path, enabling both guided exploration and user-driven discovery.

† This work was supported by a PhD grant funded by the PNRR, M4C1–Investment 3.4 "Digital Transitions", DM 118/2023.

DOI: 10.2312/dh.20253186

A central innovation of our approach is the content designer's ability to define customizable learning paths. Each node on the path represents a learning activity, such as a quiz, video, reading, puzzle, or AR-enhanced encounter, focused on a specific cultural theme or concept. The system dynamically unlocks subsequent nodes based on user interactions, engagement levels, and AI-driven recommendations, enabling personalized, theme-based cultural journeys. This structure supports both linear and non-linear narratives, giving curators and educators fine-grained control over the pedagogical flow while allowing for user agency and variation.

The underlying architecture facilitates real-time adaptation through behavioral analytics, reinforcement learning, and context-sensitive recommendations. It also supports multimodal interaction, accessible design [Spi19], and integration with external cultural datasets and ontologies. Designed to be interoperable and extensible, this framework lays the foundation for long-term sustainability and adoption in various CH domains, from museums and archaeological sites to city-scale heritage trails.

By combining serious gaming principles, AI-driven personalization, and immersive AR storytelling within a unified, scalable architecture, this work contributes a novel blueprint for the future of interactive CH experiences. Our goal is to support not only deeper visitor engagement, but also inclusive, playful, and meaningful connections to hidden treasures of our cultural heritage.

2 Background and Motivation

2.1 Gamification in Cultural Heritage: Opportunities and Limitations

Gamification has increasingly been used in Cultural Heritage (CH) to enhance user engagement, motivation, and educational impact. By incorporating elements such as rewards, challenges, and progression tracking, serious games have proven effective in transforming heritage exploration into interactive and participatory experiences. Marques et al. [MPA23] and Khan et al. [kMAO22] emphasize the capacity of gamification to foster creativity, emotional connection, and long-term engagement in CH contexts. Çetin and Erbay [ÇE21] highlight its growing presence in museums and tourism, where game-based interactions are used to mediate learning and discovery.

However, despite its promise, gamification in CH is still often characterized by limited personalization, static content, and a lack of scalable or reusable design frameworks [MPA23]. Many implementations rely on fixed game mechanics and linear experiences that do not adapt to user individual interests, learning styles, or cultural backgrounds. Furthermore, current solutions rarely offer educators or curators the tools to easily create or modify learning experiences, making sustainability and content scalability a significant challenge [Tri23].

2.2 AI for personalization and storytelling in Cultural Contexts

Artificial Intelligence (AI), especially in the form of generative models and recommender systems, has emerged as a powerful enabler of personalized digital experiences [AIK24]. In the CH domain, AI can support adaptive storytelling, real-time content generation, and user behavior modeling [Gîr24]. Trichopoulos [Tri23] and Casillo et al. [CCG*24b] explore how large language models (LLMs) and natural language processing can generate context-aware narratives and translations, offering multilingual and tailored experiences to diverse audiences.

Beyond content generation, AI techniques such as reinforcement learning, clustering, and user profiling enable dynamic adaptation of content based on preferences, behavior, and learning goals. These technologies are increasingly being applied in educational settings [MVJ22], but their use in CH remains limited and often disconnected from interactive systems. Moreover, while AI-driven personalization shows promise, there are still concerns related to transparency, explainability, and the validation of AI-generated historical content [TPFG24].

2.3 Augmented Reality in Cultural Heritage experiences

Augmented Reality (AR) has gained traction as a medium for immersive cultural and educational experiences [BBG*22]. By overlaying digital information on physical spaces, AR enables users to visualize reconstructions of historical artifacts, explore intangible heritage, and interact with contextual multimedia narratives. Bekele et al. [BPF*18] provide a detailed survey of AR in CH, noting its impact on learning effectiveness and user satisfaction. Applications such as those described by Panou et al. [PRDM18] have demonstrated the utility of mobile AR to guide visitors through cultural sites through spatial tracking and multimedia enhancement.

However, AR systems in CH often remain constrained by technical limitations, such as reliance on marker-based tracking [FPP*23], and lack deep personalization. Most AR-based CH applications function as static guides rather than dynamic systems capable of responding to user behavior, interests, or real-time interactions [BBG*22]. Although integration with AI or gamification is increasingly explored, many current AR-based CH applications still offer only preliminary or limited implementations of these features [BHA*24].

2.4 Gaps in the Integration of Gamification, AI, and AR for Personalized CH Experiences

Despite significant progress in the individual application of gamification, AI, and AR within CH, their seamless integration into a unified adaptive framework remains an open challenge. Existing systems typically implement these technologies in isolation, missing the opportunity to exploit their synergies. Ribeiro et al. [RSL*24] explore the potential of combining AR and gamification in museums, yet lack an architectural foundation for dynamic, personalized interaction.

Our work addresses this gap by introducing a reference architecture [CMV*10] that integrates gamification, generative AI, and AR to support path-based adaptive learning paths for cultural exploration. Unlike previous solutions, our approach allows content designers to define thematic educational paths in which each node, quiz, video, reading, or AR experience is dynamically unlocked and adapted based on user engagement and preferences. Inspired by frameworks like PolyGloT. [BGF*24], we apply this model to the CH domain, enabling scalable, phygital, and personalized heritage journeys.

3 System overview and Design Principles

This work presents a modular reference architecture for designing personalized cultural heritage serious games, integrating gamification, AI, and augmented reality to create immersive and educational user experiences. Building upon the principles outlined in Section 2, the platform transforms cultural visits into adaptive user-centered journeys shaped by real-time behavior, preferences, and educational goals.

At its core, the system transforms a cultural heritage visit into an interactive journey of discovery, shaped by real-time decisions, challenges, and narratives. Users are not passive recipients of information, but active participants in a dynamically evolving experience. This is made possible by the integration of adaptive content delivery, gamification strategies, and spatially-aware interactions, organized around the metaphor of a cultural treasure hunt.

Visitors engage with Points of Interest (POIs), physical or virtual markers associated with cultural artifacts, locations, or concepts. Each POI serves as a gateway to an activity, such as solving challenges, watching videos or reading cultural content, unlocking a short narrative, or exploring augmented reconstructions (see Fig. 5). As visitors interact with these activities, the system interprets their behavior and progressively shapes the remainder of their experience, building a non-linear exploration journey by dynamically adapting traversal through a predefined path-based learning path.

The adaptive traversal of path-based activities in our system follows a structure that can be naturally mapped to a Markov Decision Process (MDP), where nodes are states, transitions represent actions, and rewards stem from engagement signals and task success [CVLJ11]. While the current prototype uses rule-based heuristics to select the next activity, the modular architecture supports future integration of reinforcement learning policies.

Unlike traditional museum apps or heritage guides, this platform is not just a digital layer on physical space: it is an interactive, pedagogically informed environment. A key design rationale is to offer users a sense of agency while also supporting intentional learning, using principles drawn from informal learning theory, interactive storytelling, and educational game design. To support these goals, several guiding design principles, extracted from the literature, were adopted:

- **User-Centric Adaptivity**: The experience adapts to individual learning styles and engagement patterns, offering different types of content and challenges based on inferred preferences and past behavior [MVJ22].
- **Layered Interaction**: Cultural content is delivered in multiple modalities (visual, textual, spatial, and conversational) supporting a wide range of learning modes and cognitive levels [May14].
- **Meaningful Gamification**: The elements of the game are not just decorative, but carefully aligned with cultural themes and educational objectives to sustain curiosity, reinforce learning, and promote deep engagement [DDKN11].
- **Flexibility for Educators**: Content creators can define thematic *learning paths* using a visual authoring environment, controlling the pedagogical rhythm while allowing user-driven exploration [Tri23].
- **Immersive Spatial Context**: Augmented Reality elements are used to anchor learning in the physical space, enhancing contextual understanding and reinforcing place-based storytelling [BHA*24].

This system is not a single-purpose application, but a framework adaptable to a variety of cultural contexts, from museum exhibits to outdoor heritage trails. By bridging physical and digital heritage through adaptive learning and playful interaction, the platform aims to increase accessibility, deepen engagement, and promote a more personal connection to cultural knowledge.

4 Architecture and Components

The architecture supporting the proposed system is designed to enable adaptive, multimodal, and pedagogically meaningful interactions within cultural heritage experiences (see Fig 1). This section presents the system's technical foundation, describing how its main components—such as the mobile app, gamification engine, AI module, AR subsystem, and authoring tools—work together to create a cohesive and adaptive cultural heritage experience.

4.1 Modular architecture

The system is built on a *modular architectural framework* designed to support *adaptability*, *extensibility*, and *integration* across diverse cultural heritage contexts [MM25]. This modularity underpins all aspects of the platform, from content delivery and user interaction to personalization and data management, allowing each functional component to operate independently while remaining interconnected through a shared communication infrastructure.

At the core of the system lies a *microservices-based architecture* [HSA*23], which decomposes the overall functionality into a set of loosely coupled services. Each module, such as the mobile application, the gamification engine, the AI personalization layer, or the AR subsystem, is developed and maintained as an autonomous unit with clearly defined responsibilities. This design facilitates not only scalability and maintainability, but also rapid prototyping and integration of new features without disrupting the rest of the system.

The *modular design* is further enhanced by the adoption of asynchronous event-driven communication. Instead of relying on tightly bound, synchronous interactions, system components communicate through asynchronous event streams. These events, such as user actions, completed tasks, or state transitions, are published and consumed by various modules in real time. This architecture supports dynamic responsiveness, reduces latency, and ensures that the user experience remains fluid and uninterrupted, even as the system adapts to new inputs or conditions [RNGD22].

A key benefit of this modular and *event-based approach* is the system's ability to personalize and expand. For example, the AI module can subscribe to relevant behavioral data and independently recommend personalized learning paths, which are then consumed by the mobile interface. The gamification engine reacts to user achievements, updating progression, and triggering predefined new

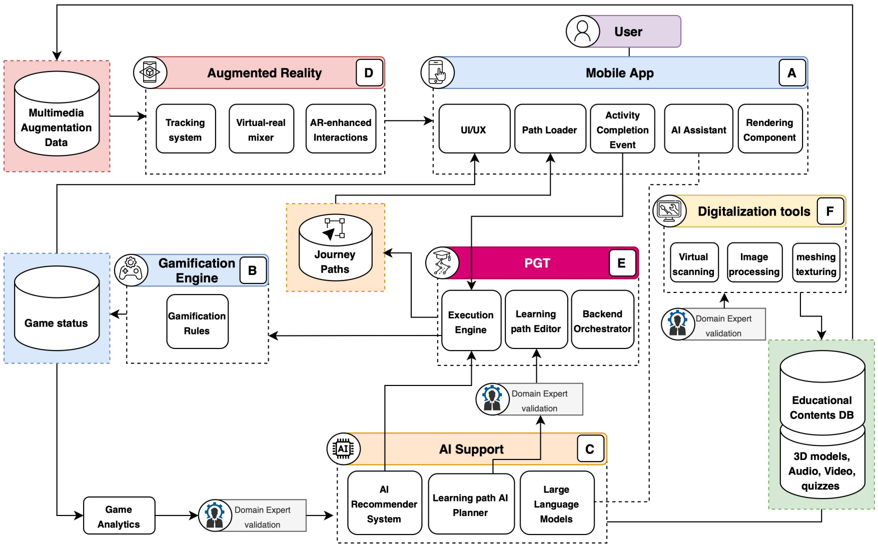

Figure 1: *The proposed reference architecture of the system.*

challenges without direct calls to the application layer. This decoupling of components ensures that enhancements in one part of the system do not necessitate changes in others, promoting long-term sustainability and facilitating collaborative development across domains.

Moreover, the architecture is designed with *interoperability* in mind. External cultural datasets, digital repositories, or educational tools, such as PolyGloT to create learning pathways, can be integrated through APIs and adapters without compromising the system's internal logic. This makes the platform suitable for deployment in varied institutional settings, from local museums to city-scale heritage trails, and supports future extensions that incorporate multilingual support, analytics dashboards, or collaborative user modes.

This foundation not only supports current functionalities, but also provides a framework for the iterative development of advanced features and expanded cultural experiences.

4.2 The Mobile App

Within the overall architecture, the *mobile application* (see Fig. 1.A) represents the central access point for users, integrating multiple back-end services to deliver a seamless and adaptive experience. Acting as the front-end layer of the system, it is responsible for presenting content, capturing user input, triggering system events, and orchestrating the user's progression through the interactive learning environment. As such, it is closely connected to the *gamification engine*, the *PolyGloT*, *AI personalization module*, and the *augmented reality subsystem*, allowing real-time responsiveness and synchronization throughout the system.

The application structures the user journey through an adaptive traversal through predefined learning paths model, where each node corresponds to a content-rich activity and each transition is driven by user behavior, system recommendations, or predefined pedagogical rules. While the learning path is statically authored in the `learning path editor` component (see Fig. 4), the traversal through it dynamically adapts based on user behavior, engagement, and AI-driven recommendations. The app visualizes the current state of this journey, showing completed activities, available POIs, and recommended next steps in a way that supports both exploration and reflection (see Fig 2.c).

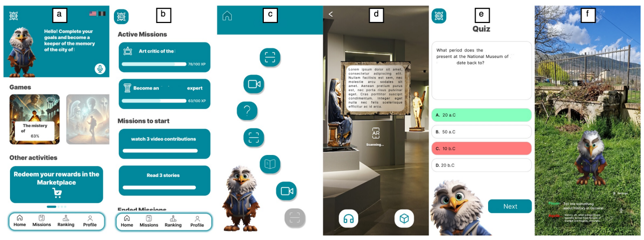

Figure 2: *Screenshots from the App. From left to right: The Home Page, the game status page, the journey page, the AR visualizations of artifacts, an example of a Quiz and the AR AI assistant.*

From an architectural perspective, the mobile app also functions as a mediator between physical and digital layers. It interprets location data, scans markers, and detects spatial triggers to deliver the appropriate content in context (see Fig. 2.d). These events are broadcast to other components via the event-driven infrastructure, ensuring that actions such as answering a quiz or interacting with an AR object are immediately reflected in the user model, reward system, and adaptive pathway.

The application is also designed to support multimodal interaction and content delivery, including visual media, narrative text, quizzes, and AR overlays. It handles low-latency rendering tasks locally, while delegating computationally intensive tasks such as recommendation generation or user modeling to the cloud-based backend. This hybrid client-server approach optimizes performance, minimizes latency, and ensures a fluid user experience across different devices and network conditions.

As the architectural interface that binds together all other components, the mobile application plays a foundational role in shaping the user's educational and cultural experience. It not only delivers content but also captures and interprets behavior, making it a critical node within the broader system responsible for enabling personalization, interactivity, and immersion.

4.3 Gamification Engine

The *Gamification Engine* (see Fig. 1.B) is designed to structure user engagement and maintain motivation throughout the cultural exploration experience. Operating as an independent module, it interfaces with the mobile application, the AI personalization engine, and the backend content model. Together, these connections deliver a consistent and rewarding user journey grounded in educational game mechanics.

From an architectural standpoint, the gamification engine is implemented as a modular service capable of managing a wide variety of interactive logic and reward structures. It defines and enforces the `gamification rules` that govern user progression, including the allocation of points, unlocking of new content, completing challenges and achieving milestones. These rules are expressed through a domain-specific language (DSL), which allows content creators—such as curators, educators, or designers—to define game logic independently from the underlying software code [BMMF23]. This separation of concerns supports flexibility, maintainability, and rapid iteration across different CH contexts.

The engine listens for events triggered by user interactions captured through the mobile application, such as discovering a POI, completing a quiz, or interacting with AR content. These events are processed asynchronously through the system's event-driven infrastructure, allowing the gamification engine to evaluate conditions, apply scoring rules, and update the user's progression state without introducing latency or interrupting the interactive flow.

In terms of integration, the gamification engine communicates closely with the AI module. Engagement data such as user choices, completion rates, and challenge outcomes are forwarded to the personalization engine, which uses them to refine recommendations and dynamically adjust the user `journey path`. This tight coupling ensures that game-based incentives are not isolated from pedagogical intent, but instead reinforce meaningful learning behaviors and exploration strategies.

Furthermore, the engine supports the visualization of progress and achievements within the mobile application. Feedback mechanisms, such as progress bars, badges, and reward notifications, are rendered in real time, enhancing user awareness of their own learning process and fostering a sense of accomplishment (see Fig. 2.b). These mechanisms are not purely motivational but are designed to highlight the thematic and educational value of each completed activity, creating a bridge between game dynamics and cultural understanding.

The gamification engine plays a vital architectural role in linking user interaction with pedagogical structure. It contributes to the personalization, adaptivity, and depth of the experience, ensuring that each interaction is both rewarding and aligned with the educational and cultural objectives of the system.

4.4 AI for Personalization, Narrative Adaptation, and User Assistance

The *artificial intelligence module* (see Fig. 1.C) plays a pivotal role in enhancing both the educational and experiential dimensions of the system, operating across three complementary layers: runtime personalization, content generation during authoring, and user assistance through a dedicated AI-driven conversational agent.

At runtime, the AI module personalizes the traversal through predefined learning paths authored in the PolyGloT framework [BGB*24].While the structure of the learning pathways remains fixed, the AI dynamically recommends the most contextually and pedagogically appropriate next node among the available options (see Fig 1). These recommendations are informed by real-time analysis of user interaction data, including responses to activities, time on task, navigational choices, and engagement patterns. By adapting the sequencing of activities to each user's preferences and learning profile, the system ensures a personalized and cognitively supportive exploration of cultural heritage, without modifying the core educational design.

In addition to runtime adaptation, the AI module supports the authoring process through the `Learning Path AI planner` within the PolyGloT environment by facilitating content generation. Leveraging museum-specific datasets and generative AI models, it can propose expert-supervised educational resources for each node—such as quizzes, readings, descriptive explanations, and contextual prompts—tailored to the specific artifacts, exhibitions, or historical themes selected by curators. This functionality accelerates the development of rich and coherent learning paths while preserving pedagogical rigor.

A further key innovation is the integration of an `AI-driven Assistant` within the mobile application. Trained on institution-specific datasets, the assistant allows users to pose free-form questions related to artifacts, historical contexts, or thematic narratives encountered during their visit (see Fig 2.f). By delivering contextually relevant, accurate, and personalized responses, the `AI Assistant` deepens visitor engagement and enables real-time exploration beyond the predefined activities. This architecture empowers each museum or cultural institution to personalize its informational offer, ensuring that the assistant reflects the specific curatorial voice and educational mission of the hosting organization.

Architecturally, the AI module operates as a scalable, cloud-based microservice interacting asynchronously with the `execution engine`, the mobile application, and the authoring environment through the system's event-driven backbone. This modular design ensures high responsiveness, scalability, and compliance with data privacy regulations.

4.5 Augmented Reality Subsystem

The augmented reality subsystem (see Fig. 1.D) is the component responsible for delivering immersive and embodied interactions within the physical or reconstructed cultural environment. Archi-

Proceedings published by Eurographics - The European Association for Computer Graphics.

tecturally, it operates as a specialized service integrated with the mobile application, responding to spatial and contextual triggers to overlay digital content onto real-world surroundings. It functions not only as a presentation layer but as an interpretive interface that deepens user engagement and supports situated learning.

The AR `tracking system` component activates when a user reaches a designated Point of Interest (POI), either through GPS-based positioning, visual marker detection, or QR code scanning. Upon activation, it retrieves the associated digital augmentation—such as a 3D reconstruction of a historical site, a visual annotation of an artifact, or a short contextual animation—and renders it through the `virtual-real mixer` component in real time through the user's device. These experiences are carefully curated to maintain alignment with both the educational objectives of the system and the thematic coherence of the current user journey.

The content rendered by the AR subsystem is retrieved from a centralized expert supervised `multimedia augmentation data repository`, which stores a wide range of visual and spatial assets in formats optimized for mobile rendering. The rendering pipeline is handled locally on the device to ensure low latency and stable performance, while metadata synchronization and trigger logic are managed centrally. This hybrid processing model ensures that users can access high-quality immersive content even in bandwidth-constrained environments, such as remote heritage sites.

Integration with other components is facilitated through the shared event-driven infrastructure. When a user completes an `AR-enhanced interaction`, the event is broadcast to the gamification engine, which updates progress and rewards.

Overall, the AR subsystem serves as a bridge between the physical and the digital, augmenting spatial context with layered cultural interpretation. It enhances the sense of presence and place, supports multimodal engagement, and contributes to the emotional and cognitive depth of the cultural experience [GRPVHBFP23]. By embedding interactive storytelling and visual learning into the user's physical surroundings, the subsystem reinforces the core vision of the platform: a personalized, exploratory, and immersive journey through cultural heritage.

4.6 PolyGloT for Adaptive Learning Path Orchestration

The *PolyGloT* subsystem (see Fig 1.E) enables the authoring, execution, and personalization of adaptive learning pathways. As both a design-time and runtime component, PolyGloT bridges pedagogical intent with interactive execution, supporting educators and curators in defining structured, gamified, and responsive learning experiences within the cultural heritage domain.

Architecturally, the subsystem consists of three interconnected modules: the `Learning Path Editor`, the `Execution Engine`, and the `Backend Orchestrator`. The `Learning Path Editor` provides a visual interface to model educational journeys as directed pathways, where nodes represent activities, such as quizzes, AR tasks, or reflective prompts, and edges define progression logic through validation conditions. This editor abstracts complex logic into user-friendly constructs, allowing non-technical authors to define personalized pathways and embed game-like mechanics, such as branching choices and reward triggers, aligned with the educational narrative.

At runtime, the `Execution Engine` governs the user's progression through the learning path. When a learner completes an activity, their interaction is evaluated via edge-defined validation logic (e.g., pass/fail conditions), compiled into executable code. The engine then determines the next viable activity based on the learner's input and contextual factors, enabling adaptive sequencing within the authored structure. This behavior is tightly integrated with the platform's event-driven infrastructure, allowing the execution logic to emit learning state events, update user models, and trigger gamification rewards.

The `Backend Orchestrator` maintains consistency between the authored path and its execution. It manages validation rules, tracks progression, and supports dynamic content delivery in the mobile app. This modularity ensures that PolyGloT can accommodate a wide range of interaction modalities while preserving a consistent pedagogical framework.

4.7 Prototype Technologies

The prototype implementation builds upon a carefully selected technological stack, aligned with the modular and extensible architecture described in Section 4.1. This integration enables real-time multimodal interaction, adaptive learning guidance, gamified engagement, and personalized cultural exploration through the coordinated use of AI, AR, and backend microservices (see Fig. 3.

The *mobile application* has been developed in Unity, chosen for its cross-platform capabilities, advanced 3D rendering, and flexible integration with external services [Tec24b]. *Augmented reality* functionality is realized through Unity's AR Foundation framework [Tec24a], supporting both location-based and marker-based AR experiences. These technologies enable users to interact with immersive digital reconstructions and narrative overlays anchored to physical Points of Interest (POIs), enhancing situated learning and contextual engagement within cultural heritage environments.

Personalized user interaction is further supported by an `AI-powered assistant` based on OpenAI's GPT models, accessed via the OpenAI API [Ope24]. Fine-tuned with institution-specific datasets, the assistant delivers culturally and thematically relevant responses to free-form visitor queries. As detailed in Section 4.4, the AI assistant dynamically integrates structured user activity data—such as visited nodes, engagement metrics, and thematic preferences—captured by the gamification engine. This hybrid approach, combining structured path traversal with generative AI reasoning, enables both adaptive recommendations for subsequent exploration and enriched dialogue experiences during visits.

The *gamification engine*, deployed as a dedicated microservice, structures the motivational dimension of the system. It interprets rules defined through a Domain-Specific Language (DSL), empowering curators and educators to design progression logic, rewards, achievements, and conditional content unlocking without requiring direct programming intervention. The engine continuously updates users' gamification profiles in response to system events, providing real-time feedback that reinforces educational objectives through points, badges, levels, and personalized challenges.

Learning content—including quizzes, readings, AR models, multimedia assets, and pedagogical metadata—is stored in a unified `Educational Content Database`. Learning pathways authored using the PolyGloT framework are represented as path structures within this repository [BMFC24]. Runtime execution of these paths is managed by a specialized `Execution Engine`, which exposes APIs to the mobile application. This engine dynamically governs the `user's traversal` based on actions, system recommendations, and AI-driven personalization cues, ensuring coherent and adaptive progression through curated cultural narratives.

Component	Technology/Tool	Purpose
Mobile Application	Unity	Cross-platform app development with 3D/AR support
Augmented Reality	Unity AR Foundation	Location-based and marker-based AR rendering
Conversational AI	OpenAI GPT (fine-tuned)	Context-aware user queries and narrative assistance
Personalization Engine	Custom AI module with reinforcement learning	Adaptive content sequencing based on behavior
Gamification Logic	Domain-Specific Language (DSL)	Rule-based game mechanics for rewards and progression
Learning Path Authoring Tool	POlyGloT (custom visual editor)	Graph-based content modeling and conditional learning paths
Backend Architecture	Microservices + Event-driven middleware	Modular component and integration and scalability
Educational Content Management	Custom content database	Storage of Quizzes, AR media, narratives, and pedagogical metadata

Figure 3: *Technologies used in the Prototype.*

5 Educational Model and Personalization Strategy

Building upon the technological infrastructure described in the previous section, the educational model defines how adaptive learning principles, gamified progression, and personalized storytelling are orchestrated to enhance user engagement and knowledge acquisition.

Rooted in pedagogical principles, the system fosters a learning experience that is not only adaptive, but also meaningful and engaging. This section outlines the conceptual and instructional foundations that inform the platform's educational model. Drawing from learning theories, cognitive taxonomies, and game-based learning strategies, the model integrates personalization and content adaptation mechanisms with carefully curated learning pathways.

The educational experience is structured as a dynamic learning journey, shaped by both the actions of the learner and the instructional intentions embedded by content designers. This model supports non-linear, exploratory learning while maintaining pedagogical rigor through scaffolded challenges and context-aware feedback. The use of PolyGloT as an authoring environment, combined with AI-driven personalization and gamified structures, ensures that each user progresses through a culturally rich narrative that is also educationally purposeful.

5.1 Integration with PolyGloT for learning paths

At the core of the educational experience is the integration with *PolyGloT*, a flexible framework for creating adaptive and personalized learning paths [BGB*24]. Within the system, PolyGloT serves as the underlying orchestration tool through which educators, curators, and designers define sequences of learning activities aligned with specific cultural or cognitive goals.

As shown in Fig 4, each learning path is modeled as a path of nodes and edges, where nodes represent discrete activities—such as quizzes, AR interactions, or reflective tasks—and edges encode conditional logic or pedagogical flow. PolyGloT allows authors to design these paths visually, using an intuitive interface that supports abstraction, reuse, and integration with multiple delivery platforms. This visual programming model facilitates rapid path creation while maintaining pedagogical control over content sequencing and adaptation.

The integration ensures that learning paths are not static but responsive, capable of evolving based on user progress, preferences, and feedback. PolyGloT also provides authoring support through AI-based suggestions, enabling the generation of learning activities or reordering of path segments based on instructional intent or learner behavior patterns observed across sessions. As such, it serves both as a design-time tool for structuring educational logic and as a runtime service enabling intelligent adaptation.

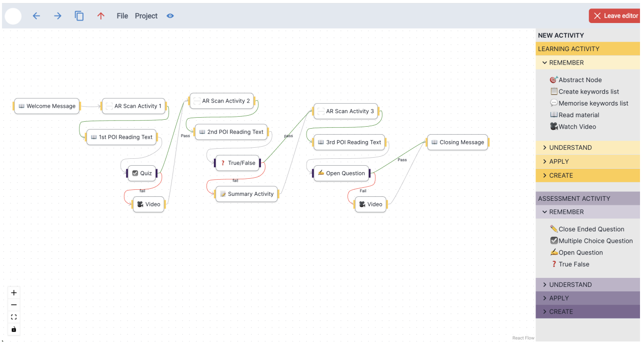

Figure 4: *The PolyGloT design tool for learning path definition.*

5.2 Pedagogical logic: Bloom alignment, task types

To support intentional learning progression, the system's activities are aligned with *Bloom's taxonomy* [Kra02], ensuring cognitive variety and appropriate scaffolding across the user journey. Each activity node within a learning path is tagged with a cognitive level—ranging from knowledge recall to evaluation and creation—which guides both content delivery and adaptive path design (see Fig. 4).

This structure allows the system to differentiate between lower-order tasks, such as factual identification or basic comprehension, and higher-order challenges that involve comparison, critical thinking, or creative interpretation. As users progress through the journey, the task complexity can be adjusted to match their cognitive engagement and demonstrated proficiency, fostering deeper understanding and sustained motivation.

The activity types themselves are intentionally diverse, supporting a broad spectrum of learning modalities. These include multiple-choice quizzes, AR-enhanced visual analysis, narrative prompts, exploration-based tasks, and comparative assessments. Each activity is paired with contextual media and interaction strategies that reinforce its instructional goal while also maintaining thematic immersion in the cultural content. The modular nature of the system allows these tasks to be recombined in different configurations depending on the user profile and learning objective.

5.3 AI-Driven Personalization and Adaptive Learning Paths

The proposed system leverages AI-driven personalization to optimize each visitor's educational journey through the cultural-heritage experience. Rather than altering the structure of the learning pathways, the AI dynamically adapts the *traversal* within predefined path-based learning paths designed by cultural experts, thereby balancing structured educational objectives with flexible, user-centric progression.

Each activity node in the path is annotated with pedagogical metadata aligned with Bloom's taxonomy [BGB*24]. Cognitive levels-ranging from basic knowledge acquisition to comprehension, application, and analysis-are assigned during the authoring phase (see Fig. 4). Designers retain full agency: a toggle in the editor allows them to override or correct any automatically suggested Bloom level, ensuring alignment with their instructional intentions.

The AI module then uses real-time interaction data to recommend the most suitable next node, supporting both *remediation*—by routing learners who show low engagement or repeated errors to lower-complexity tasks—and *upward scaffolding*, gradually promoting them to higher-order activities as proficiency improves. If a visitor fails an *Apply*-level twice, the engine offers an *Understand*-level explanatory video, awards a small encouragement badge, and-after a successful checkpoint quiz-unlocks a new *Analyse*-level challenge.

This adaptive flow augments rather than replaces the curator's design, delivering a responsive experience that remains faithful to cultural narratives and learning goals while giving educators fine-grained control over cognitive complexity.

5.4 Gamified Educational Model

Gamification in the system serves not merely as a motivational overlay but as a structural element of the learning process itself. Game mechanics such as progression, feedback, rewards, and challenges are mapped to pedagogical strategies that support exploration, reflection, and mastery. The gamification engine enforces a reward structure that aligns with educational goals. Points are awarded not only for task completion but also for depth of engagement, for instance, spending more time in reflective activities, exploring optional content, or revisiting complex material. Badges and achievements correspond to thematic milestones or cognitive accomplishments, helping users visualize their own learning trajectory.

The system also supports adaptive gamification through rule-based logic: challenge difficulty, progression pacing, and reward timing are adjusted based on predefined conditions tied to user behavior. This allows the gamified experience to remain motivating without becoming either trivial or overwhelming. Leaderboards, collaborative quests, or narrative branching paths can be introduced in specific deployments, depending on the institutional context and audience needs.

By embedding game mechanics into the learning structure, rather than treating them as superficial incentives—the platform fosters sustained engagement while reinforcing the educational integrity of the experience. Users are not merely playing to win but playing to learn, reflect, and connect more deeply with cultural narrative learning pathways.

6 Prototype Application and Use Case

A preliminary prototype of the system has been developed to validate the core architectural and pedagogical concepts presented in this work. While the current version has not yet undergone formal testing with end users, it provides a functional demonstration of the integrated components, establishing the foundation for iterative refinement and future deployment in a real-world cultural heritage context. In Figure 6 it is possible to see the development status of the prototype elements.

The prototype targets a use case situated in the National Museum of Abruzzo (MuNDA) and its surrounding archaeological park. The cultural site includes a set of thematically rich Points of Interest (POIs) distributed across both indoor and outdoor environments, making it an ideal scenario to test the system's capacity for location-based storytelling, augmented reality integration, and adaptive learning paths. The aim is to enhance visitors' exploration of the site by turning the experience into a personalized cultural journey, dynamically by users' preferences, knowledge levels, and engagement patterns.

Currently, the prototype supports the main functional elements of the system (see Fig 5). Users interact through the *mobile application*, which delivers location-aware activities such as quizzes, multimedia content, and AR visualizations. These are linked to POIs that can be activated via marker scanning. Each activity is designed as a node within a learning path authored through PolyGloT, enabling the definition of flexible and thematic learning paths aligned with cultural narratives and pedagogical goals.

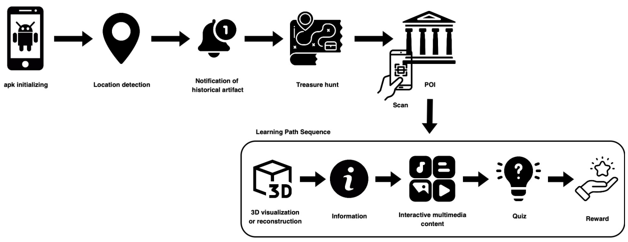

Figure 5: *User interaction flow in the gamified cultural heritage application. After location-based detection and artifact notification, users engage in a treasure hunt and scan Points of Interest (POIs) to unlock AR visualizations, contextual information, interactive content, quizzes, and educational rewards.*

While the *personalization engine* and *gamification module* are both integrated, their logic is currently limited to predefined rules and scripted conditions. At this stage, AI personalization is implemented using predefined conditions and scripted adaptations, with future development aimed at real-time, behavior-driven personalization. While limited to predefined rules, this version validates core interactions and architectural viability, laying the foundation for future AI-driven adaptivity. Future development will focus on refining the AI-driven adaptation flow, allowing for more nuanced personalization based on real-time user modeling and behavioral data. Similarly, the *AR subsystem* presently offers a limited set of digital augmentations, which will be expanded to include more immersive and interactive content in alignment with the final curatorial narrative.

The prototype is being internally evaluated to assess technical stability, content alignment, and narrative coherence. These evaluations will inform the next development cycle, during which improvements will be made to the user interface, task variety, and feedback mechanisms. The goal is to prepare the system for pilot deployment with actual museum visitors, enabling a full-scale user study that will measure learning impact, engagement, and usability.

Feature	Implemented	Notes
Mobile App	Yes	Core learning graph
Gamification	Partially	Rule-based
AI Personalization	Partially	Rule-based logic, no live ML yet
AR Subsystem	Yes	Marker-based POIs
PolyGloT	Yes	Definition and execution of learning paths

Figure 6: *The Prototype realization status.*

6.1 Prototype Performance and Deployment

To benchmark runtime performance in a museum-like setting, we compiled a release build of the app using UNITY 2022.3 LTS and AR FOUNDATION 5.1, deploying it on a *Samsung Galaxy Tab S9+* (Snapdragon 8 Gen 2, 12 GB RAM, Android 14). This setup allowed us to test real-time responsiveness, AR fluency, and offline behavior.

- **LLM round-trip time:** the average round-trip time for a single GPT-3.5-Turbo query $\sim$ 880 ms on Wi-Fi (70 Mbps, 25 ms median ping); $\sim$ 1.5 s on congested 4G.
- **AR framerate:** 50 fps at 720p with stable marker tracking.
- **App bundle size:** 250 MB, including preloaded offline assets.
- **Minimum device specs:** $\geq$ 4 GB RAM, Android 10 or iOS 14.

To address unreliable connectivity in cultural venues, the app features a fallback mode: if the LLM or leaderboard is unavailable, it answers queries via a local QA cache or fallback templates. Interactions and scores are stored in an encrypted local `SQLite` database and synchronized with the backend when the connection is restored, ensuring continuity and data integrity.

7 Conclusion and future work

This paper has presented the design and early implementation of a modular, AI-enhanced serious game platform for personalized cultural heritage exploration. By integrating gamification, adaptive learning pathways, and augmented reality within a cohesive pedagogical framework, the system aims to transform heritage visits into engaging and educational journeys tailored to each user's interests and learning style.

The proposed architecture supports real-time personalization, multimodal interaction, and pedagogically driven content sequencing. The integration with PolyGloT empowers content designers to build flexible and thematically coherent learning paths, while the AI module ensures that these paths are dynamically adapted based on user behavior. The gamification engine further reinforces motivation and progression through meaningful reward structures aligned with cognitive goals.

Although the system has not yet been tested with end users, the current prototype validates the technical feasibility of the platform and demonstrates its potential to support adaptive and immersive cultural heritage experiences. It also provides a stable foundation for expanding the content, refining the personalization mechanisms, and conducting empirical evaluation in a real-world setting.

Future work will focus on several parallel directions. First, the prototype will be enhanced through iterative design cycles, informed by internal testing and curator feedback. This includes expanding the AR content, improving the authoring workflows, and integrating more advanced AI-driven adaptation strategies. Second, we plan to conduct pilot studies in collaboration with cultural institutions, evaluating the system's usability, educational impact, and user engagement across diverse audiences. Finally, further research will investigate how the system can support collaborative learning scenarios and multilingual experiences, expanding its applicability across different cultural and educational contexts.

References

[AIK24] AYEMOWA M. O., IBRAHIM R., KHAN M. M.: Analysis of recommender system using generative artificial intelligence: A systematic literature review. *IEEE Access* (2024). 2

[BBG*22] BOBOC R. G., BĂUTU E., GÎRBACIA F., POPOVICI N., POPOVICI D.-M.: Augmented reality in cultural heritage: an overview of the last decade of applications. *Applied Sciences 12*, 19 (2022), 9859. 2

[BG20] BUGEJA M., GRECH E. M.: Using technology and gamification as a means of enhancing users' experience at cultural heritage sites. *Rediscovering Heritage Through Technology: A Collection of Innovative Research Case Studies That Are Reworking The Way We Experience Heritage* (2020), 69–89. 1

[BGB*24] BUCCHIARONE A., GINI F., BONETTI F., BASSANELLI S., SCHIAVO G., MARTORELLA T., ADAMI F., GUIDOLIN T., ZAMBOTTO L.: Can generative ai support educators? creating learning paths with polyglot. In *General Aspects of Applying Generative AI in Higher Education: Opportunities and Challenges*. Springer, 2024, pp. 393–428. 5, 7, 8

[BGF*24] BUCCHIARONE A., GUIDOLIN T., FASOL L., SCHIAVO G., KIENZLE J., GERARD S., NÉGRIER D., MARTORELLA T.: Polyglotuml: A gamified framework for enhancing uml learning paths. In *Proc. of the ACM/IEEE 27th International Conference on Model Driven Engineering Languages and Systems* (2024), pp. 31–35. 2

[BHA*24] BAKAR J. A. A., HANAFI E. H. M., ABIDIN R. Z., PENDIT U. C., ARSHAD H.: Augmented reality meets artificial intelligence towards personalised user experience in cultural heritage sites. In *The Future of Human-Computer Integration*. CRC Press, 2024, pp. 134–148. 2, 3

[BMFC24] BUCCHIARONE A., MARTORELLA T., FRAGERI D., COLOMBO D.: Polyglot: A personalized and gamified etutoring system for learning modelling and programming skills. *Science of Computer Programming 231* (2024), 103003. 7

[BMMF23] BUCCHIARONE A., MARTELLA S., MUCCINI H., FUSCO M.: Dsl4gar: A domain specific language for gamification rules definition, simulation and deployment. *Simulation and Deployment* (2023). 5

[BPF*18] BEKELE M. K., PIERDICCA R., FRONTONI E., MALINVERNI E. S., GAIN J.: A survey of augmented, virtual, and mixed reality for cultural heritage. *Journal on Computing and Cultural Heritage (JOCCH) 11*, 2 (2018), 1–36. 2

[BPSP21] BRONZIN T., PROLE B., STIPIĆ A., PAP K.: Artificial intelligence (ai) brings enhanced personalized user experience. In *2021 44th International Convention on Information, Communication and Electronic Technology (MIPRO)* (2021), IEEE, pp. 1070–1075. 1

[CBJK21] CARLTON J., BROWN A., JAY C., KEANE J.: Using interaction data to predict engagement with interactive media. In *Proc. of the 29th ACM International Conference on Multimedia* (2021), pp. 1258–1266. 1

[CCG*24a] CAPECE S., CHIVĂRAN C., GIUGLIANO G., LAUDANTE E., NAPPI M. L., BUONO M.: Advanced systems and technologies for the enhancement of user experience in cultural spaces: an overview. *Heritage Science 12*, 1 (2024), 71. 1

[CCG*24b] CASILLO M., COLACE F., GUPTA B. B., LORUSSO A., SANTANIELLO D., VALENTINO C.: The role of ai in improving interaction with cultural heritage: An overview. *Handbook of Research on AI and ML for Intelligent Machines and Systems* (2024), 107–136. 2

[ÇE21] ÇETIN Ö., ERBAY F.: Gamification practices in museums. *Journal of Tourismology 7*, 2 (2021), 265–276. 2

[CMV*10] CLOUTIER R., MULLER G., VERMA D., NILCHIANI R., HOLE E., BONE M.: The concept of reference architectures. *Systems Engineering 13*, 1 (2010), 14–27. 2

[CVLJ11] CHI M., VANLEHN K., LITMAN D., JORDAN P.: An evaluation of pedagogical tutorial tactics for a natural language tutoring system: A reinforcement learning approach. *International Journal of Artificial Intelligence in Education 21*, 1-2 (2011), 83–113. 3

[DDKN11] DETERDING S., DIXON D., KHALED R., NACKE L.: From game design elements to gamefulness: defining" gamification". In *Proc. of the 15th international academic MindTrek conference: Envisioning future media environments* (2011), pp. 9–15. 3

[FPP*23] FANINI B., PAGANO A., PIETRONI E., FERDANI D., DEMETRESCU E., PALOMBINI A.: Augmented reality for cultural heritage. In *Springer Handbook of Augmented Reality*. Springer, 2023, pp. 391–411. 2

[Gîr24] GÎRBACIA F.: An analysis of research trends for using artificial intelligence in cultural heritage. *Electronics 13*, 18 (2024), 3738. 2

[GRPVHBFP23] GÓMEZ-RIOS M. D., PAREDES-VELASCO M., HERNÁNDEZ-BELEÑO R. D., FUENTES-PINARGOTE J. A.: Analysis of emotions in the use of augmented reality technologies in education: A systematic review. *Computer Applications in Engineering Education 31*, 1 (2023), 216–234. 6

[HA11] HABGOOD M. J., AINSWORTH S. E.: Motivating children to learn effectively: Exploring the value of intrinsic integration in educational games. *The Journal of the Learning Sciences 20*, 2 (2011), 169–206. 1

[HSA*23] HOSSAIN M. D., SULTANA T., AKHTER S., HOSSAIN M. I., THU N. T., HUYNH L. N., LEE G.-W., HUH E.-N.: The role of microservice approach in edge computing: Opportunities, challenges, and research directions. *ICT Express 9*, 6 (2023), 1162–1182. 3

[kMAO22] KHAN I., MELRO A., AMARO A. C., OLIVEIRA L.: Role of gamification in cultural heritage dissemination: A systematic review. In *Proc. of Sixth International Congress on Information and Communication Technology: ICICT 2021, London, Volume 1* (2022), Springer, pp. 393–400. 2

[Kra02] KRATHWOHL D. R.: A revision of bloom's taxonomy: An overview. *Theory into practice 41*, 4 (2002), 212–218. 7

[LIR24] LUO F., ISA M. I., ROOSLI R.: Research status and development direction of smart heritage: A bibliometric review (1994-2024). *Journal of Asian Architecture and Building Engineering* (2024), 1–24. 1

[May14] MAYER R. E.: Incorporating motivation into multimedia learning. *Learning and instruction 29* (2014), 171–173. 3

[MCB*14] MORTARA M., CATALANO C. E., BELLOTTI F., FIUCCI G., HOURY-PANCHETTI M., PETRIDIS P.: Learning cultural heritage by serious games. *Journal of Cultural Heritage 15*, 3 (2014), 318–325. 1

[MM25] MARTUSCIELLO F., MUCCINI H.: Mundar: An ai-driven, gamified augmented reality framework for cultural heritage exploration. *ERCIM News 2025*, 141 (2025). 3

[MPA23] MARQUES C. G., PEDRO J. P., ARAÚJO I.: A systematic literature review of gamification in/for cultural heritage: leveling up, going beyond. *Heritage 6*, 8 (2023), 5935–5951. 2

[MVJ22] MUNIR H., VOGEL B., JACOBSSON A.: Artificial intelligence and machine learning approaches in digital education: A systematic revision. *Information 13*, 4 (2022), 203. 2, 3

[NBB*20] NELSON B. C., BOWMAN C. D., BOWMAN J. D., PÉREZ CORTÉS L. E., ADKINS A., ESCALANTE E., OWEN B. L., HA J., SU M.: Ask dr. discovery: The impact of a casual mobile game on visitor engagement with science museum content. *Educational Technology Research and Development 68* (2020), 345–362. 1

[Ope24] OPENAI: Openai api documentation, 2024. Accessed April 2025. URL: https://platform.openai.com/docs. 6

[PRDM18] PANOU C., RAGIA L., DIMELLI D., MANIA K.: An architecture for mobile outdoors augmented reality for cultural heritage. *ISPRS International Journal of Geo-Information 7*, 12 (2018), 463. 2

[RNGD22] RAHMATULLOH A., NUGRAHA F., GUNAWAN R., DARMAWAN I.: Event-driven architecture to improve performance and scalability in microservices-based systems. In *2022 International Conference Advancement in Data Science, E-learning and Information Systems (ICADEIS)* (2022), IEEE, pp. 01–06. 3

[RSL*24] RIBEIRO M., SANTOS J., LOBO J., ARAÚJO S., MAGALHÃES L., ADÃO T.: Vr, ar, gamification and ai towards the next generation of systems supporting cultural heritage: Addressing challenges of a museum context. In *Proc. of the 29th International ACM Conference on 3D Web Technology* (2024), pp. 1–10. 2

[SF11] SCHOENAU-FOG H.: Hooked!–evaluating engagement as continuation desire in interactive narratives. In *Interactive Storytelling: Fourth International Conference on Interactive Digital Storytelling, ICIDS 2011, Vancouver, Canada, November 28–1 December, 2011. Proc. 4* (2011), Springer, pp. 219–230. 1

[Spi19] SPINA C.: Wcag 2.1 and the current state of web accessibility in libraries. *Weave: Journal of Library User Experience 2*, 2 (2019). 2

[Tec24a] TECHNOLOGIES U.: Ar foundation, 2024. Accessed April 2025. URL: https://docs.unity3d.com/Packages/com.unity.xr.arfoundation. 6

[Tec24b] TECHNOLOGIES U.: Unity real-time development platform, 2024. Accessed April 2025. URL: https://unity.com. 6

[TPFG24] TIRIBELLI S., PANSONI S., FRONTONI E., GIOVANOLA B.: Ethics of artificial intelligence for cultural heritage: Opportunities and challenges. *IEEE Transactions on Technology and Society* (2024). 2

[Tri23] TRICHOPOULOS G.: Large language models for cultural heritage. In *Proc. of the 2nd International Conference of the ACM Greek SIGCHI Chapter* (2023), pp. 1–5. 2, 3

[XRBM14] XHEMBULLA J., RUBINO I., BARBERIS C., MALNATI G.: *Intrigue at the Museum: Facilitating Engagement and Learning through a Location-Based Mobile Game.* ERIC, 2014. 1