A Reconfigurable Framework for the Virtual Reconstruction of Ancient Egyptian Rituals: The Case of the *Cippi* of Horus

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Ancient Egyptian rituals relied on the use of objects believed to possess magical properties, as well as on gestures and recitations. Unfortunately, these rituals are often studied today through museum artifacts and magical texts, presented without the sequence of actions, participants, and spatial settings that gave them contextual meaning. From a historical perspective, reconstructing these elements is useful for establishing hypotheses about how a ritual may have been performed and how its components related to one another. It also constitutes a valuable resource for museums to enhance ancient artifacts and improve visitors' understanding of their role and meaning within ritual performance. This paper introduces a modular 3D system for reconstructing ancient rituals as interactive digital performances. The approach is grounded in a structured, JSON-based data model that formalizes actors, artifacts, spatial anchors, and stepwise ritual structures, and it is intentionally authored through spreadsheets so that domain experts can iterate the ritual reconstruction without programming. By decoupling ritual definition from application code, the framework supports rapid revision, reuse across scenarios, and explicit representation of alternative ritual pathways. We evaluate the system through a case study of the *Healing Ritual with the Cippi of Horus*, based on fourth-century BCE inscriptions associated with the Metternich Stela. The pipeline generates Unity scenes with motion-captured performances, audio-based spoken texts, and dynamic prop handling. It also supports branching structures to model ritual variability. Results show that data-driven simulation can function as a practical research tool for specifying ritual performances and for analyzing the intangible aspects of ancient tangible heritage. However, animation authoring and gesture synchronization remain a major bottleneck, as some interactions must be managed through data and code, increasing effort.

CCS Concepts: • **Applied computing → Performing arts**; • **Computing methodologies → Computer graphics**.

Additional Key Words and Phrases: Digital humanities, Intangible Cultural Heritage, Egyptology, Ancient Egypt, Magic

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1 Introduction

Ancient Egyptian magical practices were fundamentally performative, integrating divine invocation and magical formulae (*logos*), symbolic action (*praxis*), and specific material contexts, to address afflictions such as disease or physical danger. While many of the objects associated with these rituals, such as the *cippi* of Horus, are preserved in museum collections, their presentation is typically static. This creates a significant limitation in interpretation, as the performative, spatial, and temporal aspects that provided these objects with their supposed original power are often absent or remain highly speculative in traditional exhibitions. Consequently, there is a clear need for digital tools that can effectively communicate these intangible practices.

This paper proposes a modular system designed to reconstruct ancient rituals as dynamic and interactive experiences. Central to this approach is a structured data model, encoded via JSON files, which serves as the primary mechanism for ritual formalization and automated scene generation. Unlike traditional 3D reconstructions that are often hard-coded and thus fixed, our system employs a data-driven pipeline where the ritual structure, including actors, spatial configurations, and narrative paths, is decoupled from the underlying software execution. This paper explicitly addresses the following questions:

(1) How can a modular 3D pipeline, driven by a structured JSON data model, enable domain experts to reconstruct ritual performances (with non-linear branching pathways) without programming knowledge?
(2) How can these immersive reconstructions function as tools for visualizing and disseminating different ritual hypotheses?

The main contributions of this work are threefold:

- A modular authoring workflow that translates a structured JSON-based data model into interactive 3D environments, allowing for the rapid reconfiguration of ritual components. The JSON input can be generated from simple spreadsheets, thus facilitating the collaborative design of the ritual among domain experts.
- A detailed case-study reconstruction of the *Healing Ritual with the Cippi of Horus*, drawing on an extract from the text inscribed on the Metternich Stela (4th century BCE) as the ritual's *logos*.
- A framework for the preservation and visualization of intangible cultural heritage (ICH) that focuses on the integration of gesture, speech, and movement in a historically-grounded environment.

A key aspect of our methodology is the rigorous distinction between archeological evidence and interpretative inference. The material elements, such as the iconography of Horus the Child and the specific spells found on Horus *cippi* , are well-documented in the primary sources. However, the procedural order and exact movement paths of the ritual practitioners often require comparative reasoning and expert interpretation. The proposed data model addresses this uncertainty by supporting variability and branching logic; for instance, the system can simulate different ritual pathways based on alternative hypotheses. By encoding these variants directly into the JSON schema, the system allows researchers to represent multiple interpretive hypotheses within a single digital environment.

The remainder of this paper is organized as follows. Section 2 reviews previous work in the fields of digital humanities and performative heritage reconstruction. Section 3 provides the historical and cultural background for the healing ritual and the Horus *cippi* . Section 4 details the system architecture, the underlying data model, the workflow, and the runtime implementation. Section 5 verifies the system through the specific use case of a healing ritual performed with a Horus *cippus*, specifically the one conserved at the Museu Egipci de Barcelona. Finally, Section 6 concludes the paper and outlines directions for future work.

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2 Previous work

The reconstruction of ancient ritual practices requires an interdisciplinary approach situated at the intersection of digital humanities, archeological visualization, and procedural narrative design. This section reviews recent developments in virtual heritage, performance capture, and authoring pipelines.

2.1 Virtual Heritage and Immersive Reconstruction

The transition from static museum exhibitions to interactive 3D experiences has fundamentally altered the preservation and interpretation of cultural heritage [23]. Current research emphasizes the re-contextualization of fragmented artifacts through immersive media, allowing researchers to explore spatial relationships that are otherwise inaccessible [20, 34]. While high-fidelity visualization is often the primary focus, some authors have argued for the importance of methodological transparency and adherence to established standards for quality digital content [8, 9]. Immersive environments such as Virtual Reality (VR) and Mixed Reality (MR) provide platforms for testing ritual hypotheses by simulating dynamic processes within historical or hypothetical contexts [23, 29].

2.2 Intangible Cultural Heritage and Performance Capture

Intangible Cultural Heritage encompasses the performative dimensions of artifacts, including gestures, recitations, and ritual performance [3]. Reconstructing these dimensions is complex, as ritual objects often lose their interpretive context when removed from their original settings [19]. Performance-based projects have sought to restore these dynamics; for example, the *Virtual Egyptian Temple* utilized virtual environments to investigate the spatial aspects of liturgical texts [15], while *The Egyptian Oracle* integrated live actors with a virtual temple to restore the sensory and dramatic aspects of ancient ceremonies [16]. While these projects demonstrate the value of multi-sensory storytelling [7, 37], a recurring challenge remains the accurate synchronization of captured movement with underlying ritual logic [44].

2.3 Procedural Scene Generation

Recent developments in procedural 3D pipelines have sought to automate the creation of immersive environments from structured descriptions [2, 13, 33]. Current research in full-body motion synthesis and human-object interactions aims to generate realistic movements based on task goals, such as grasping or manipulating ritual props [14, 38]. While these systems provide significant technical capabilities, the translation of qualitative historical data into structured machine-readable formats remains a bottleneck for domain experts.

2.4 Authoring Tools for Non-Programmers

To empower domain experts in the reconstruction process, recent work has focused on developing ”expert-in-the-loop” interfaces. Tools such as *Inceptor* utilize natural language processing to generate social VR scenarios from text [25], while *ConnectVR* employs trigger-action interfaces for designing agent-based stories [5]. Other systems, such as *EntangleVR*, explore visual programming as a means to reduce the technical barriers for non-programmers [4]. These frameworks highlight the importance of modularity and accessibility, but they often lack the fine-grained control over ritual branching and historical metadata required for rigorous validation.

2.5 Egyptology-Specific Digital Projects

The *Digital Giza* project provides an extensive archive linking 3D models with excavation records and inscriptions [39]. Similarly, the *Constructing the Sacred* initiative utilizes visibility analysis and architectural modeling to examine the sensory landscapes of the Saqqara necropolis [35, 36]. The *Pervival Project* allows visitors to

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understand the museum collection through an interactive virtual environment as a complement to the panels distributed throughout the museum [20].

Recent collaborations between the Museo Egizio and Politecnico di Torino have further refined these immersive approaches. By utilizing 3D digital reconstructions and VR, researchers have addressed the hypothetical original placement of the Sekhmet statues, allowing visitors to navigate different configurations through interactive "pulsating icons" that trigger historical narrations [34]. This shift towards experiential dimensions is also seen in work incorporating photogrammetry and acoustic simulation to understand tomb visitation [1]. While these projects excel at spatial reconstruction, the systematic encoding of performative ritual variability remains a research challenge. Wheeler [46] emphasizes that ancient Egyptian rituals must be approached as live performances, highlighting the need to consider embodied action alongside textual and visual evidence.

This paper builds upon the modular logic seen in previous authoring systems [18] but shifts the focus toward a JSON-driven data model tailored for historical ritual reconstruction. While existing research often prioritizes simplified trigger-action narratives, our approach provides a structured framework that explicitly encodes ritual branching, actor synchronization, and evidence-based metadata. By decoupling the ritual structure from the technical implementation, our system contributes a reusable pipeline for researchers to test and visualize interpretive hypotheses regarding the intangible performative aspects of ancient Egyptian artifacts.

3 Historical-Cultural Context

This section provides the Egyptological framework for the digital reconstruction, focusing on the material and performative characteristics of the healing ritual.

3.1 Ritual Background

The primary instrument of the ceremony we chose as a test case is the *cippus* of Horus, a type of magical stela frequently employed during the last millennium BCE (between Dynasties XXII–XXVI) and which gained prominence during the Late Period [43]. Although this kind of artifact can be traced from the Eighteenth Dynasty, the Horus *cippus* acquired a standard form between the late New Kingdom and the Third Intermediate Period that continued into Roman times, albeit with some iconographic modifications [11]. These objects served as protective or curative devices for persons who had suffered attacks from venomous animals. Their modern designation derives from the iconography carved on them: Horus the Child subduing dangerous creatures (snakes, scorpions, lions, and oryx) grasped in his hands while he stands atop of a couple of crocodiles or more, symbolizing his dominion over chaotic forces [40]. Examples survive in various sizes, from large stelae, such as the Metternich Stela, measuring 84 cm in height (Figure 1a), to medium (approx. 30 cm) and small ones (5–30 cm). Some specimens contain a perforation at the upper edge, presumably enabling them to be worn as pendants. Several scholars have proposed that magicians may have carried them suspended around the neck among their customary ritual paraphernalia when visiting patients. The smaller examples may have functioned primarily as amulets [31], serving to protect their bearer, particularly during travel.

The use of such objects is intrinsically connected with the mythological cycle of Horus the Child (Harpokrates), the son of Isis and Osiris, pursued by his uncle Seth, the slayer of Osiris. Isis and the young Horus took refuge in the marshlands of the Delta, a liminal and protective landscape. During one of Isis's absences, the child Horus was bitten by a scorpion, an event that triggered a crisis of cosmic significance. Isis's cries of anguish caused the solar barque of Re to halt as it passed nearby. The god Thoth descended from the barque and, through his knowledge and magical expertise, healed Horus. From this episode onward, Horus became the archetype of the divine figure who conquered venom and venomous animals, and thus the paradigm of the savior.

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(a) (b)

Fig. 1. Elements of the ritual context: (a) Metternich stela, XXX Dynasty, Metagraywacke 52.6 kg, MMA 50.85 (The Metropolitan Museum of Art, photo by Anna-Marie Kellen); (b) Healing statue, Ptolemaic period, Grauwacke, H. 67,7 cm, Louvre E 10777 (Musée du Louvre, Dist. GrandPalaisRmn / Georges Poncet).

Horus *cippi* are inscribed with spells and mythological narratives, most notably the story of Thoth healing Horus from a venomous wound, which serves as the archetypal foundation for the ritual [40], and are carved on all surfaces: recto, verso, sides, and even the base. The mask of Bes positioned at the top serves to repel dangerous beasts and malevolent forces through its fearsome aspect and the hypnotic power of its gaze. In later examples, an increasingly prominent Bes mask is depicted, occupying much of the available surface as this deity came to be regarded as progressively more powerful and effective.

The *cippi* could be immersed in water contained within basins inscribed with magical formulae. The water thereby absorbed the magical power of the texts and divine images with which it had come into contact. Another procedure involved pouring water or oil over the *cippus* and collecting it in a basin or small container. The liquid was then ready (imbued with *heka*) to be applied to the wound or consumed by the patient in need of healing from venomous bites. It is also plausible that healing involved direct rubbing contact, as suggested by the pronounced erosion visible on several examples, particularly on the front, that is, on the figure of Horus himself. It remains unclear whether the magician manipulated the *cippus* or whether it was placed directly against the patient's body at the site of injury. The heavy wear visible on some pieces suggests repeated use over long periods. A magician could inherit such an object from a predecessor, thus incorporating it into his regular ritual toolkit [31]. These gesture-related possibilities in the ritual benefit from our tool's ability to represent multiple ritual pathways.

On the other hand, Horus *cippi* could be integrated into a supporting statue representing the donor of the stela. Healing was effected by drinking water poured over both the statue and the *cippus* and then collected in basins at the statue's feet, which were likewise inscribed with magical formulas. Virtually the entire surface of this type of statue is covered with inscriptions or images, with the exception of the face, hands, and feet. A particular statue of a priest of Bastet (Figure 1b) explicitly describes its own mode of use, leaving no doubt that the healing process operated through water contact with the magical texts. The donors of the *cippus* (the priests of Bastet) are depicted directly above it. The figure bearing the stela functions as their representative. The healing statue could be placed within a temple chapel dedicated specifically to this theme. The ensemble was intended for public use, serving the collective benefit.

In the *sanatorium* at Dendara (Figure 2), socket holes and at least one base covered with magical formulae have been discovered; these structures likely supported statues bearing Horus *cippi*. The associated texts suggest that patients bathed in the water that had been poured over these healing statues.

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Fig. 2. *Sanatorium* of Dendara, Graeco-Roman Period (Photo: Núria Torras-Benezet).

In the ritual reconstruction we propose, the procedure is highly modular and depends on the severity of the patient's condition. The reconstruction accounts for four primary healing methods identified in the sources: (1) direct application of the *cippus* to the wound, (2) drinking water that has been consecrated by flowing over the stela, (3) applying oil similarly charged with magical efficacy, and (4) ritual bathing in water treated by a large-scale healing statue [43].

The ritual 3D reconstruction involves three primary categories of actors:

- **The Pure Priest of Sekhmet (*wab*):** The lead officiant who must maintain strict ritual purity to serve as a conduit for divine power [42]. He is depicted wearing a *shendyt* kilt and carrying symbols of authority, such as an ebony staff and a *kherep* scepter [42].
- **The Client:** Typically an individual of high-social standing seeking relief from disease or venomous stings. The client participates by presenting offerings and exposing the afflicted body part to the ritual action.
- **Acolytes:** Priest assistants who manage ritual objects, provide libations, and burn incense to maintain the ceremonial atmosphere [42].

3.2 Spatial Setting

The 3D reconstruction situates the ritual within a dedicated chapel, such as the sanctuary of the goddess Hathor in the temple of Ptah at Karnak [34]. This temple (see Figure 3), constructed under Thutmose III (1479–1425 BC, Eighteenth Dynasty), is situated at the northern boundary of the sacred domain of Amun-Re in Karnak [41]. Evidence for the existence of an earlier sanctuary, whose date remains undetermined, is preserved in two inscriptions found within the current structure [41].

In its original configuration, the Ptah temple was located outside the Eighteenth-Dynasty *temenos* of the Amun-Re complex; however, the enlargement of the enclosure during the Thirtieth Dynasty brought the Ptah sanctuary within the extended sacred perimeter [41]. The mud-brick enclosure wall was erected less than one meter from the northern façade of the Thutmose III building, severely restricting lateral access from the north and likely impeding several aspects of the temple's daily activities [41]. This spatial constraint accounts for some important Ptolemaic modifications introduced on the western side of the courtyard. After its abandonment, the temple was occupied by a Coptic community, from the fifth to sixth centuries CE, whose settlement activities led to a significant reduction and alteration of the original pharaonic brick walls and subsidiary structures [41].

The Hathor chapel, where we propose the development of the 3D digital reconstruction of the healing ritual, is one of the architectural elements of the oldest remaining area of the temple of Ptah. This area consists of a

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Fig. 3. Temple of Ptah, Karnak (Upper Egypt), Thutmose III-Roman period (CFEETK-CNRS-MoA: J.-Fr. Gout).

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triple-cell structure built by Thutmose III. The central chamber is dedicated to Amun-Re, as the temple functioned as a way-station for the barque of the god during his annual processions, which continued until the Roman Period [41]. This main chamber provides access to two chapels: one for Hathor on the southern side, and one for Ptah on the northern side. In front is a portico with two polygonal columns opening onto the small courtyard that was modified in Ptolemaic times [41].

Inside the Hathor chapel, the spatial configuration proposed in the digital reconstruction is centered around an altar and a libation table where the *cippus* is placed . The original environment was designed to be multi-sensory, incorporating smoke from incense censers and chants to establish a spiritual atmosphere.

Specific spatial requirements for the 3D model include, in the chapel of Hathor :

- **The Altar:** An alabaster structure serving as the primary site for offerings and the placement of the *cippus* of Horus.
- **The Basin:** An inscribed font used to collect oil or the water poured over the *cippus*.
- **Cult Images:** A statue of Sekhmet and a statuette of Thoth placed in relation to the altar to represent the divine presence overseeing the healing process. This statue of Sekhmet was found in fragments in the southern chapel of the temple in 1901/02 [6]. Its actual location appears to be corroborated by Georges Legrain's affirmation: « *Quelques jours après, dans le sanctuaire d'Hathor, nous trouvions les nombreux fragments de la déesse léontocéphale que nous avons depuis raccommodée et remise en place* » [6].

3.3 Temporal Setting

The temporal setting is primarily defined by the Metternich Stela, which dates to the 4th century BCE during the 30th Dynasty [40]. This period represents a peak in the production and use of *cippi* for protective and curative purposes. More broadly, the Late Period witnesses a marked intensification of magical practices, reflected in the substantial proliferation of amulets, healing statues, and magico-religious papyri. The wider dissemination of these artifacts does not reflect a spiritual crisis at all. Instead, it seems to point to a democratization of magico-religious prerogatives, which earlier had led to the progressive spread of funerary literature from the restricted royal context to common individuals [30]. In line with this trend, non-royal private tombs from the Late Period show an increase in funerary artifacts, such as *ushebtiu*, at the expense of objects associated with daily life.

In our simulation, at a finer scale, the temporal dimension is expressed through the chronological sequence of ritual acts: the initial petition, libations and purification, the core healing ritual (recitation and actions) and the

final sealing of protection via the delivery of a miniature talismanic *cippus* to the client. As in ancient Egyptian ritual practices, objects served to focus attention, materialize spells, and culminate or seal rituals [43].

3.4 Methodological Considerations and Interpretive Limits

Translating the historical, spatial, and temporal frameworks detailed above into an interactive 3D simulation inevitably raise important methodological questions concerning uncertainty, interpretation, and historical reliability. Unlike architectural or artifacts reconstructions, which are often grounded in substantial material remains, virtual reconstructions of rituals must frequently rely on the integration of heterogeneous sources, including texts, iconography, archaeological evidence, and comparative analogies. As a result, many aspects of ritual performance (including the precise sequence of actions, some gestures, movements, participants' roles, vocalization, tempo, and spatial dynamics) remain partially or entirely speculative. Projects such as the *Virtual Egyptian Temple* and *The Egyptian Oracle* have demonstrated the value of immersive reconstructions as research tools, but they also highlight the interpretative choices necessarily involved in translating fragmentary evidence into coherent performative scenarios [15, 16].

Rather than providing definitive representations of the past, virtual reconstructions should therefore be understood as hypothesis-driven models that make explicit the assumptions underlying particular interpretations. Their scholarly value lies not only in visualization but also in their capacity to test alternative scenarios, identify evidential gaps, and foster critical discussion about the nature and limits of our knowledge of ancient ritual practices. This perspective is particularly relevant in the study of ancient Egyptian rituals, where textual prescriptions, material evidence, and actual performance often cannot be directly matched. Consequently, transparency regarding sources, degrees of certainty, and interpretative decisions becomes a fundamental requirement for ensuring the scholarly credibility and reproducibility of virtual ritual reconstructions.

The reconstruction of the *Healing Ritual with the Cippi of Horus* involves several layers of uncertainty that must be explicitly acknowledged. Although the inscriptions preserved on Horus *cippi*, particularly those of the Metternich Stela, provide detailed information regarding the spells, mythological narratives, and therapeutic intentions and actions of the ritual, they do not offer a complete description of its actual performance. Furthermore, textual prescriptions may not necessarily reflect actual practice. Discrepancies between instructions contained in magical manuals and the archaeological evidence of magical artifacts suggest that practitioners adapted rituals to specific circumstances, including the nature of the illness, the availability of raw materials, and the economic and social status of their clients [43]. Consequently, the virtual reconstruction presented here should not be understood as a definitive representation of a historical event, but rather as a historically informed interpretative model based on the best available evidence.

4 Ritual Reconstruction Method

The proposed system is conceived as a research and communication tool that allows for the formalization and visualization of performative rituals through a data-driven pipeline, where Egyptologists can rely on conventional tools (e.g., spreadsheets) to define or adjust the different aspects of the ritual.

4.1 Design Requirements

The primary requirement of the system is to provide an "expert-in-the-loop" authoring environment where Egyptologists can modify the ritual reconstruction without programming skills [25]. To achieve this, the system emphasizes:

- **Decoupling of ritual logic and execution:** Ritual choreography, branching paths, and spatial configurations are defined in external data files, independent of the Unity3D source code.

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- **Tabular Authoring:** Use of familiar spreadsheet interfaces to manage complex metadata and temporal sequences, lowering the technical barrier for domain experts [5].
- **Modularity and Reusability:** Ensuring that environments, actors, and ritual steps can be swapped or reconfigured to test different historical hypotheses [34].

4.2 Process Overview

As illustrated in the workflow diagram (see Figure 4), the process is divided into seven functional blocks: (1) Historical Research, (2) Asset Creation, (3) Initial Authoring, (4) Motion Capture, (5) Final Scripting, (6) Preprocessing via Python, and (7) Unity Simulation.

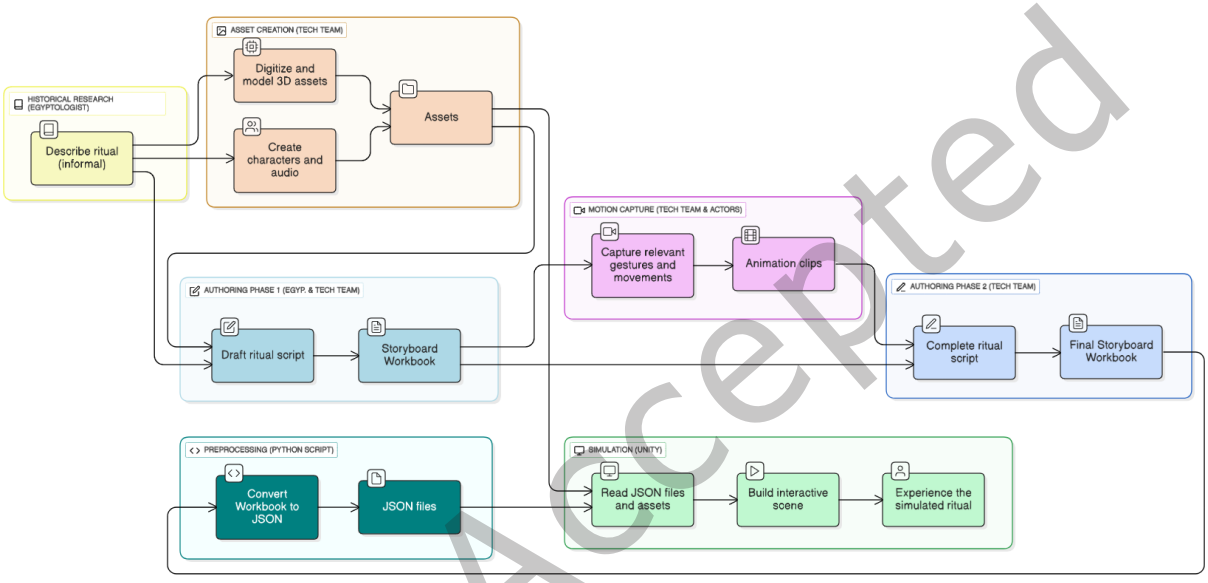


Fig. 4. Workflow diagram illustrating the phases from historical research to 3D simulation.

This seven-stage pipeline organizes the transition from qualitative historical research to automated 3D simulation by acting as a bidirectional bridge. While blocks (1), (2), and (4) focus on the acquisition of historical evidence and digital assets, blocks (3), (5), and (6) function as a formalization layer where this information is integrated into the data model.

By separating the data acquisition tracks from the narrative authoring, the framework ensures that updates in historical interpretation or the addition of new archeological findings can be integrated without restructuring the application's core architecture. This modularity provides the necessary technical foundation for the iterative refinement process and the authoring tools detailed in the following sections.

4.3 Data Model

Originally, the project's output was envisioned as a graphical adventure where rituals were represented as a series of static poses and discrete scenes. While the system evolved toward dynamic animation, the underlying model retains this discrete structure, organizing the ritual into a set of entities that can be authored independently and then composed at runtime into a coherent, time-based performance.

The underlying conceptual model of a ritual is shown in Figure 5. A ritual is represented as a hierarchical structure composed of Acts, which are, in turn, decomposed into ordered PlaySteps. Branches support alternative

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progressions within the ritual, while each PlayStep is situated in an Environment and may include a CharacterAction or trigger a CameraMotion. CharacterAction entities capture the physical dimension of performance, including character movement between Places, the execution of AnimationClips, and Object manipulation.

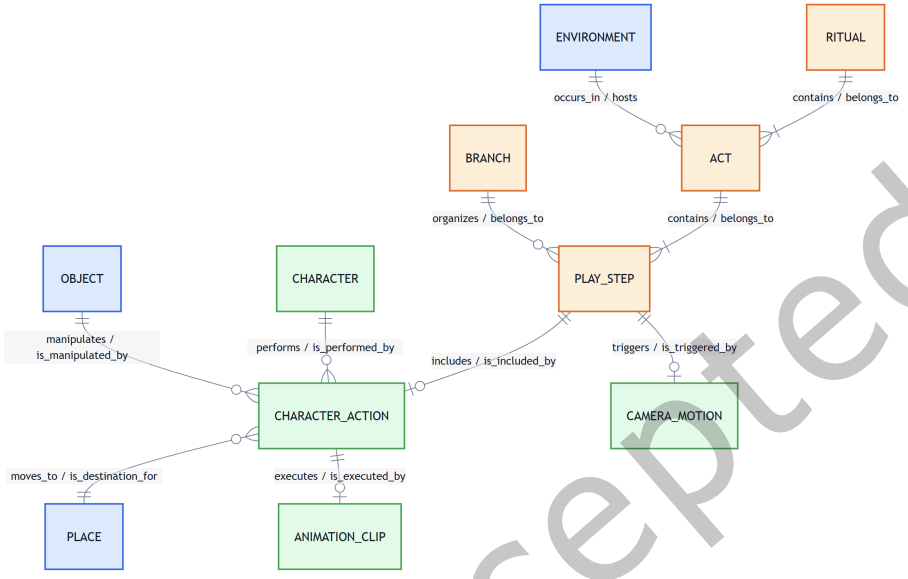


Fig. 5. Conceptual model of the ritual system. Background colors group entities by role: orange denotes the narrative structure (Ritual, Act, PlayStep, Branch), green indicates runtime performance elements (Character, CharacterAction, AnimationClip, CameraMotion), and blue designates entities related to the spatial and physical context (Environment, Place, Object).

The JSON files used in our implementation adopt a slightly simplified version of the conceptual model described above, reflecting the fact that their contents are generated automatically from a collection of spreadsheets containing the detailed description of the ritual. The current implementation uses a couple of JSON documents with multiple top-level collections (e.g., Characters, Places, Objects, Play) whose elements are linked by identifiers.

- **Actors and Characters:** Definitions of ritual participants, including their names, descriptions, and 3D models (e.g., Priest Yuny, Client Nesuhor).
- **Objects and Artifacts:** Digital representations of ritual objects, categorized as static (altars, statues) or dynamic (stelae, bowls, scepters).
- **Spaces and Places:** Spatial data including the general Environment (e.g., Temple of Ptah) and specific Places (anchors for character positioning).
- **The Play:** A chronological list of narrative units defining which character performs which animation, their dialog, and the camera's target.
- **Branching Logic:** A set of conditional paths (branches) that allow the simulation to represent different ritual outcomes based on aspects such as the patient's status or the user's choices in game-like experiences.

A significant challenge in this model is animation synchronization. Because actors were recorded separately, the files must explicitly define frame-level correspondences (AnimSyncs) to align interactions like the handing over of a stela or the pouring of water [43]. In the following, we detail each entity type, its principal attributes, and the relationships that ensure the ritual remains both modular and computationally tractable.

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RitualInfo. RitualInfo contains bibliographic and curatorial metadata used for UI labeling and provenance (e.g., Title, Description, Date). While not used to generate scenes directly, it anchors the simulation to a specific scholarly object of study and can be extended with citations, museum inventory numbers, or alternative titles.

Music. Music is a registry of audio tracks that can be referenced by play nodes or used as continuous ambience. Each entry provides an Id (stable key), and descriptive fields such as Title. In practice, the Id is resolved to an audio asset in Unity.

Environments. Environments define the coarse spatial context. Each environment provides: (i) an Id referenced by places and play nodes; (ii) a Model string used to instantiate the correct 3D scene; (iii) a Unit (e.g., meters) for consistent scaling; and (iv) an Origin transform (world offset) that anchors imported geometry and supports georeferencing when needed.

Places. Places are named anchors within an environment. They represent semantically meaningful positions (e.g., *FrontOfSekhmet*) and are used to place characters and objects without requiring authors to manipulate Unity coordinates directly. Each place includes: Id (primary key), optional Title, a foreign key Environment (linking to Environments.Id), and a Location vector. The Location is interpreted as a 3D position; in some cases authors may include an extra component (e.g., a heading/yaw) to encode facing direction. At runtime, place transforms are instantiated as invisible scene anchors, and play nodes reference them through StartPos and (optionally) Target.

Objects. Objects define all manipulable and non-manipulable artifacts in the scene. Each object includes: Id (primary key), Model (Unity prefab identifier), and optional descriptive fields (Description, ExtendedDescription) that support scholarly documentation and UI tooltips. Spatial attributes include Location (initial position), Rotation (Euler angles), and Scale (vector). The boolean flag IsStatic differentiates: (a) static scenery objects (altars, statues) that remain fixed and are spawned at initialization; and (b) dynamic props (*cippi*, bowls, vessels) that can be attached to character hands and re-positioned during interactions. Domain-specific attributes (e.g., Size for physical dimensions) can be used to constrain affordances (e.g., which hand grasps are plausible) or to validate scale against real-world measurements.

Characters. Characters specify the list of characters that participate in the ritual. Each character contains: Id (primary key), optional Name, Model (avatar rig/prefab), and a Scale used to align the avatar to the environment. Rich text fields (Description, ExtendedDescription) encode iconographic and costume decisions, making interpretive assumptions explicit and reviewable (e.g., hairstyle, jewelry, ritual garments). These textual fields are also used to generate documentation and explanatory elements in the application's UI.

Animations. Animations are stored as a flat registry that associates a motion clip with a specific character. Each entry includes: Id (animation label), CharacterID (foreign key to Characters.Id), and optional performer metadata (Actor). The pair (CharacterID, Id) is treated as the unique key, enabling reuse of an animation label across multiple characters (e.g., each character can have an idle clip) while still resolving to the correct clip at runtime. The Animator component in Unity is used to play the corresponding animation clip and control a state machine that manages transitions between different animation states based on runtime parameters.

Acts. Acts provide a narrative and analytical partition of the ritual (e.g., petition, healing, sealing), similar to scenes in a play. Each act defines an Id and Title. Play nodes reference ActID to support chapter-like navigation, filtering, and comparative analysis (e.g., aligning different ritual hypotheses by act).

Play nodes (the timeline). Play is an ordered list of nodes, interpreted as a timeline of performative actions. Each node may specify:

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- ActID and SceneID: narrative grouping. SceneID is used as a lightweight clustering label (e.g., all actions taking place in ”Scene 2”).
- EnvironmentID: optional override indicating in which environment the node occurs; when omitted, the current environment is inherited.
- CharacterID: the performer of the node (foreign key to Characters.Id).
- StartPos: optional place anchor (foreign key to Places.Id) used to set or place the character at the beginning of the node. When absent, the characters remain where the previous node left them.
- Animation: an animation label resolved through Animations using (CharacterID, Animation).
- Duration: node temporal extent. In practice, a non-negative value indicates seconds to wait before advancing; special values (e.g., -1) can encode ”play full clip”.
- Dialogue and Audio: optional spoken text and an mp3 audio file identifier. If both are present, Audio is treated as the authoritative timing source and Dialogue as transcript/subtitles.
- Target: optional semantic target, typically another character (Characters.Id) or a place (Places.Id), used to drive look-at behavior or navigation goals.
- GraspingLeft / GraspingRight: declarative prop attachment for each hand. Values are either an object id (Objects.Id) or a sentinel such as Release to detach currently held objects. This abstraction allows Egyptologists to specify object-hand relationships without scripting inverse kinematics.
- CameraPos and CameraTarget: optional cinematic directives. CameraPos is a 3D position, while CameraTarget can reference an Objects.Id or Characters.Id to keep the action visible; when missing, camera control defaults to a rule-based behavior (e.g., follow performer).
- BranchID: optional tag indicating that the node belongs to a specific branch (foreign key to Branches.Id).

This design keeps the timeline authorable in a spreadsheet-like manner while still supporting rich multimodal output (motion, audio, camera) in Unity.

Branches (conditional segments). Branches define optional or alternative segments of the play. Each branch specifies: Id (primary key), StartingLine and EndingLine (indices into the Play list), and ButtonText (UI label used when prompting the user or the simulation logic). At runtime, a branch selection activates only the nodes whose indices fall within the selected interval, while nodes outside that interval are skipped. Branch membership can also be redundantly tagged per play node via BranchID, enabling validation checks (e.g., ensuring that all nodes within StartingLine..EndingLine carry the expected branch tag).

AnimSyncs (cross-actor temporal synchronization). To represent interactions recorded independently (e.g., handing an object from one actor to another), we introduce AnimSyncs as explicit synchronization constraints. These constraints define frame-level correspondences between a reference actor and a secondary performer. Rather than applying a global speed adjustment, the system uses the AnymSyncLoader to divide the secondary animation into discrete segments based on the provided sync points. The pipeline then performs a piecewise linear remapping of time, allowing for localized speed variations that ensure the actors’ hands or ritual objects meet at the exact required frame. Crucially, this offline pre-processing stage also reschedules any associated AnimEvents (e.g., object grasping) to match the new timing, avoiding the overhead and instability of dynamic speed adjustments. Furthermore, this pairwise alignment strategy enables the synchronization of three or more actors by indirectly anchoring them all to a single reference character’s timeline, ensuring global temporal consistency across complex group choreographies.

Although stored in JSON, the model behaves like a lightweight relational schema: Characters.Id, Objects.Id, Places.Id, and Environments.Id function as primary keys; play nodes reference them as foreign keys. Before Unity generation, the pipeline validates: (i) all referenced IDs exist; (ii) animation labels exist for each (CharacterID,

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Animation) pair; (iii) branch intervals fall within the bounds of Play; and (iv) grasping instructions reference dynamic objects when attachment is expected. These checks reduce ambiguity for non-programmer authors and make interpretive changes feasible, since modifications are localized to data rather than code.

A short excerpt from a JSON file describing the ritual is presented below.

```
{
    "RitualInfo": [
        {
            "Title": "Healing ritual with the cippi of Horus",
            "Description": "A ritual drama inspired by the Metternich stele (MET 50.85)",
            "Date": "IV bC"
        }
    ],
    "Objects": [
        {
            "Id": "Censer",
            "IsStatic": "False",
            "Model": "censer.fbx", ...
    "Characters": [
        {
            "Id": "Priest",
            "Name": "Yuny",
            "Description": "Sekhmet Priest", ...
    "Acts": [
        {
            "Id": "Act01",
            "Title": "The client's petition" ...
    "Play": [
        {
            "ID": "ClientArrival",
            "ActID": "Act01",
            "SceneID": "1",
            "Description": "The nobleman is at the door. The noble Nesuhor enters the sanctuary with a
            ↪  reverent attitude. He kneels before the priest. Leaning, hands extended in supplication.
            ↪  Nesuhor, with a trembling gesture, lifts his tunic and reveals his armwith a wound caused
            ↪  by a scorpion bite.",
            "Duration": "25",
            "CharacterID": "Client",
            "StartPos": "ArrivalClient",
            "Animation": "arrival",
            "Target": "Priest"
        }, ...
    ],
    "Branches": [
        {
            "Id": "A",
            "StartingLine": "18",
            "EndingLine": "19",
            "ButtonText": "May the god Horus restore order, may he be above Nesuhor's wound!"
        }, ...
    ]
}
```

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4.4 Authoring Workflow

The authoring workflow is designed to allow domain experts to define complex ritual behaviors without direct code modification. As detailed in the system architecture, this process follows a seven-block pipeline. The process begins with the Egyptologist providing an informal description of the ritual, identifying the sequence of actions, symbolic elements, and participants. This qualitative foundation is then digitized through an iterative collaboration between the expert and the technical team. During the initial authoring phase, the team drafts a ritual script within a multi-sheet "Storyboard Workbook." This workbook serves as the primary interface, organized into twelve functional sheets that conceptualize the ritual as a theatrical play. To facilitate ease of use, the spreadsheet includes dropdown menus for columns such as CharacterId and EnvironmentId, ensuring data consistency and reducing input errors.

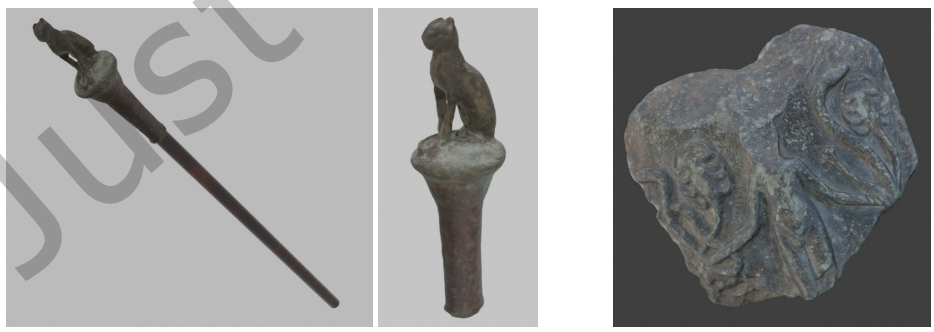
The transition from tabular data to a machine-readable format is handled by a custom Python script that parses the workbook, implementing specific validation rules such as splitting comma-separated values into lists for transformations (scale, rotation, and location) and preserving raw text for dialog fields. The output consists of two files: ritual.json, which contains the high-level logic and scene descriptions explained above, and animData.json, which stores technical frame-level synchronization data and interaction events.

A critical feature of this workflow is the support for a "review-and-revise" loop. If the resulting 3D simulation reveals historical inaccuracies or technical misalignments, the Egyptologist can modify the corresponding cell in the spreadsheet and re-run the pre-processing script. This decoupling of the ritual logic from the Unity execution layer allows for rapid hypothesis testing and the representation of branching variants, where the user can select different narrative paths within the simulation.

4.5 Asset Acquisition

The reconstruction integrates a diverse range of 3D assets to balance archeological precision with visual completeness, sourcing models from physical digitization, AI-driven synthesis, and external repositories.

4.5.1 Digitized Physical Artifacts. High-fidelity digitization of primary sources was prioritized for the main ritual objects. Two specific items from the collection of the Museu Egipci de Barcelona were processed using photogrammetry: a cane head depicting the goddess Bastet and a fragment of a *cippus* of Horus (see Figure 6). The Bastet cane was completed by modeling a simplified cylindrical shaft and applying custom textures to match the original piece.



(a) (b)

Fig. 6. 3D models generated via photogrammetry from artifacts held at the Museu Egipci de Barcelona. (a) Cane's head with the goddess Bastet; (b) Fragment of a *cippus* of Horus.

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4.5.2 Synthesized and Externally Sourced Models. To include items that were either unavailable in museum collections or lacked high-quality digital counterparts, we employed the *TRELLIS* AI-driven framework [21]. As illustrated in Figure 7, this system generated visually coherent representations for objects such as the Thoth statue, a *hes* vase, a miniature *nw* pot, and a hand censer. While these are not exact replicas, they provide the necessary spatial and symbolic context for the ritual. Additional assets were sourced from *Sketchfab* (see Figure 8), including the *Egypt Chamber* (environment), a *Sekhmet* statue from the *Museo Egizio* in Turin, and a New Kingdom papyrus scroll used as a ritual manual.

We limited the application of AI exclusively to the reconstruction of these 3D models and the dialogue audio, ensuring that the generated assets maintain sufficient coherence and closely resemble the original artifacts for which the 3D model was unavailable. While the JSON file could be fed into an AI to generate a preliminary version of the ritual for non-expert users, even if it lacks historical accuracy, we intentionally avoided employing AI for the reconstruction of the spatial environments or the ritual performance itself because, as argued by Foka and Griffin [10], current AI models lack the general cultural competency required to yield historically accurate results. Conversely, for an expert-oriented version, a specialized tool like the one presented in this work is essential, as it additionally allows for the incorporation of branches representing alternative hypotheses developed by domain experts. The bias that AI introduces into generated outputs is inherent to cultural heritage collections which AI models can further amplify. This becomes particularly evident in intangible heritage, such as magical rituals, which give rise to multiple interpretations. Fully relying on AI-generated outputs raises ethical, theoretical and social risks [12]; consequently, control over the historial narrative cannot be relegated to automated systems. It is essential to maintain a critical perspective and ensure continuous, ”expert-in-the-loop” validation of the results. Nevertheless, this technology offers substantial potential to facilitate our understanding of the past. However, closer collaboration between cultural institutions and technological partners is necessary to develop high-quality datasets for AI to achieve more precise results that can rigorously serve academic research [17].

4.5.3 Character and Motion Data. Characters were modeled using MakeHuman to reflect the physical descriptions found in Late Period iconography. For instance, the priest Yuny was inspired by the kneeling statue *MMA 33.2.1*, featuring a *shendyt* kilt and a *menat* collar [40].

Animations were captured using an *Xsens MVN Awinda* motion capture system [22]. Due to the availability of only one capture suit, each character's performance was recorded in isolation. The raw data was cleaned and retargeted using the *Rokoko* plugin for Blender before being exported to Unity as humanoid rigs to facilitate compatibility [32]. Many of the captured sequences correspond to general-purpose gestures (greetings, offerings, bows) and basic locomotion, and are therefore reusable across multiple ritual reconstructions. However, a substantially different ritual, especially one requiring specialized handling of objects or distinctive choreographic patterns, would likely require expanding the available clip library with additional motion-capture recordings.

4.5.4 Audio and Dialogue. Background music was sourced with permission from Rafael Pérez Arroyo's *Ancient Egypt: Music in the Age of Pyramids*, specifically utilizing the tracks ”The Three Seasons - Ashet” and ”Processional Hymn to Hathor” [28]. Ritual dialogs were generated using OpenAI's text-to-speech model [24].

4.6 System Structure and Implementation Details

The core of the simulation environment is built upon a direct mapping between the structured JSON data and a C# class hierarchy within Unity. This architecture ensures that the ritual logic remains independent of the software implementation, facilitating a data-driven execution of the performance.

4.6.1 C# Integration and Data Mapping. The runtime system relies on a Ritual Controller, which serves as the central manager for the simulation. This controller deserializes the ritual.json file into C# objects, such as Character, Environment, Object, and Play entries, that mirror the original spreadsheet structure.

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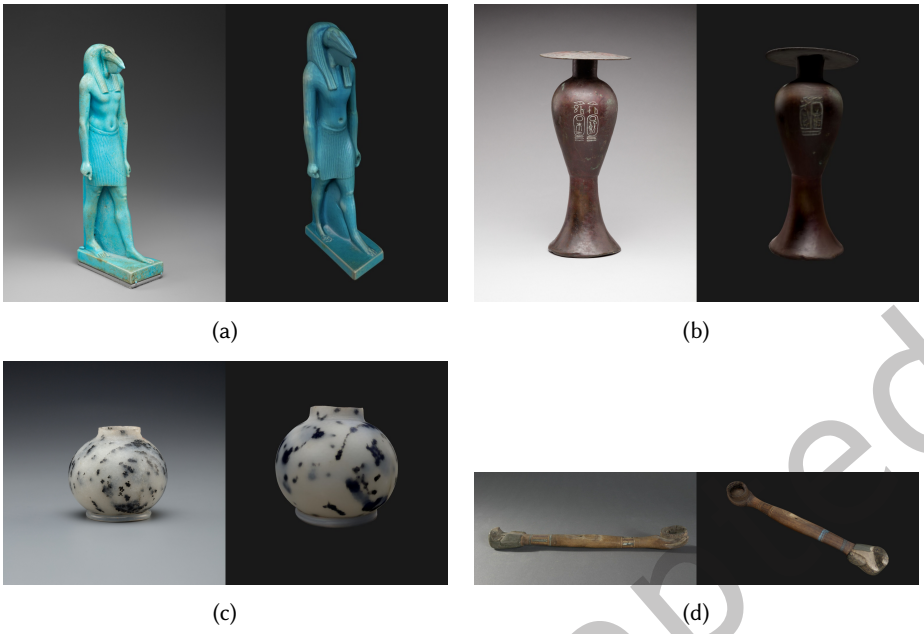


Fig. 7. Comparison of original Egyptian artifacts (left) and AI-generated reconstructions (right) using the TRELLIS framework. (a) *Striding Thoth*, Ptolemaic Period (MMA, 26.7.860); (b) *Hes Vase with the name of Ramesses IV*, New Kingdom (MMA, 59.180a, b); (c) Miniature *nw* pot, Old Kingdom (MMA, 07.228.92); (d) *Hand-held Censer*, New Kingdom (Musée du Louvre, E 14687). Original images courtesy of The Metropolitan Museum of Art and the Musée du Louvre.

4.6.2 Model Instantiation and Material Handling. An additional challenge, stemming from the decision to support externally defined objects and characters, is that the Unity project cannot simply include these elements as preconfigured scene assets. Instead, the application must load and instantiate them at runtime based on the information provided in the JSON. This introduces extra complexity because models that are typically brought into a Unity scene through the editor often require manual adjustments (e.g., scale normalization, pivot alignment, collider setup, material assignment, and rig configuration). Since the Egyptologist never interacts with the Unity editor and only uses the final executable, these adjustments must be performed automatically at runtime within the simulator application. To resolve common issues with missing materials or textures after importing 3D models (particularly the complex temple environment), we implemented a recursive method that derives texture filenames from material names, creates new materials using the Universal Render Pipeline (URP) Lit shader, and dynamically assigns the correct textures.

4.6.3 Physics and Collision Management. The system distinguishes among three primary types of entities, each with specific physical properties configured at instantiation:

- **Environments:** To enable navigation and interaction, a recursive method traverses the environment's hierarchy, automatically attaching MeshCollider components to all renderers. A kinematic Rigidbody is added at the root level to ensure the structure remains static while participating in collision detection.
- **Characters:** These entities are assigned an Animator component and a CharacterAnimEvents script to handle runtime interactions. Transformations are updated via an UpdateTransform() method, and hand-bone accessors allow for precise attachment of ritual objects.

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(a) (b) (c) (d)

Fig. 8. Externally sourced 3D assets: (a) *Statue of the Goddess Sekhmet* (Museo Egizio, CC BY 4.0), (b) *Egypt Chamber for AR & VR Games* (arloopa, Free Standard License), (c) *Papyrus Scroll (New Kingdom)* (Rollins College Archaeology, CC BY 4.0), and (d) *Pouch* (Jessie Cuvelier,CC BY 4.0). Models were adapted for use in the virtual ritual environment.

- **Objects:** Artifacts are configured with either a MeshCollider or a fallback BoxCollider. Their physical behavior is governed by the IsStatic flag in the data model; static objects remain kinematic, while dynamic objects use non-kinematic Rigidbody components to allow for realistic gravity and collision response when released or dropped.

4.6.4 Spatial and Cinematic Control. To maintain spatial consistency across diverse 3D sources, the system implements a ToLocal() coordinate transformation. This method applies a fixed origin offset, defined in the Environments sheet, to all raw coordinates, ensuring that actors and objects are correctly aligned within the temple's pivot system. Additionally, the system features an automated AutoplayCoroutine that iterates through the Play list, coordinating character positioning, audio triggers, and cinematic camera transitions. When enabled, these camera movements utilize the SmoothCameraTransition() method, which interpolates position and rotation over a fixed 1.5-second duration to provide a smooth visual transition during the ritual performance.

4.7 Information Viewer

To bridge the gap between immersive performance and historical depth, the framework incorporates an Interactive Information Viewer. This module functions as a "transparency layer" that allows users to suspend the temporal flow of the ritual and access the primary evidence behind the reconstruction.

The interface (Figure 9) is designed for intuitive navigation, divided into two primary functional zones:

- **The Entity Catalog (Left Panel):** The left side of the screen features a persistent, scrollable list of every character, object, and location present in the ritual. This catalog ensures that no detail remains hidden by the complexity of the 3D scene. Users can select specific assets ensuring that every element is discoverable regardless of its scale, position, or the current state of the simulation.
- **The Contextual Dashboard (Right Panel):** Once an entity is selected from the catalog, the right-hand panel populates with comprehensive information. Each entry replaces raw technical data with the historical context necessary for a deeper understanding of the ritual. This information is supported by

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Fig. 9. The Information Viewer displaying a selected character (*left*) and a ritual object (*right*), illustrating how contextual data and primary source records are consistently presented for all entities.

primary visual evidence that allows users to verify the digital reconstruction against historical material. An embedded 3D object turnaround player enables neutral-environment inspection of details, such as hieroglyphic inscriptions, that may be obscured in the main scene. Complementing this, static images, including photographs of museum artifacts, site-specific reliefs, or historical representations, facilitate a direct comparison between the source material and the 3D recreation.

4.8 Animation Integration

To leverage MOCAP data while maintaining the modularity of the system, we implemented a pre-processing pipeline. Since asynchronous recording often leads to misalignments in interactions, the system calculates playback speed multipliers and remaps keyframes based on the synchronization pairs defined in the data model. This ensures that, for instance, a priest's hand and a client's bowl meet at the exact frame required by the ritual logic, regardless of the original capture timing.

5 Results and Discussion

The technical verification of the proposed system focuses on the performance of the data-driven pipeline, the capacity of the authoring workflow to accommodate complex historical data, and the practical implementation of the reconstruction of the *Healing Ritual with the Cippi of Horus*.

5.1 System Features and Performance

The primary technical result is a functional 3D framework that successfully translates ritual structured data into an interactive Unity environment (see Figure 10) without manual script modifications or specific technical skills. The system effectively processed the following data derived from the case study:

- The ritual structure is organized into 12 functional sheets, defining 10 distinct entity types (Characters, Objects, Environments, etc.) and a Play sequence consisting of approximately 40 discrete steps.
- The simulation manages the real-time instantiation and transformation of four characters and over 10 interactive or static ritual artifacts, including photogrammetric and AI-generated models.
- A total of 18 motion-captured animation clips were dynamically synchronized and integrated with spatialized dialogs and a looping background music playlist.

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Fig. 10. Sequence of the three ritual acts. The process initiates with the petition (*left*), transitions into the central healing performance (*middle*), and concludes with the sealing of the ceremony (*right*).

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5.2 Technical Analysis of the Authoring Workflow

The spreadsheet-based interface achieved our design objectives of lowering technical barriers for data entry. During the implementation process, it became clear that the use of the tabular format to define ritual elements, such as character IDs, spatial coordinates, and dialog, allows for the rapid reconfiguration of the ritual without re-compiling the Unity project [25].

However, our internal testing revealed that the abstraction of performative behavior into a machine-readable format requires a higher degree of granularity than initially anticipated. For instance, achieving accuracy required the manual entry of detailed frame-level data for animation synchronization and precise coordinate offsets for object interactions. This suggests that while the system is ”expert-in-the-loop”, the authoring phase remains a time-intensive process that demands high technical precision to avoid errors.

5.3 Handling Ritual Variability and Branching

A significant achievement of the modular architecture is its robust handling of ritual variability. In the ritual reconstruction, the healing procedure varies according to the severity of the patient’s condition . The system effectively managed this through a dynamic selection panel (see Figure 11) that allows the user to trigger four distinct narrative branches in Act 02 (performative core): (a) direct application of the *cippus*, (b) drinking consecrated water, (c) applying oil, and (d) ritual bathing in the *sanatorium*.

This capability provides significant value by allowing researchers to represent and test multiple interpretive hypotheses within a single digital environment [23]. By explicitly encoding these variations into the Branches sheet of the workbook, the reconstruction can act as a transparent record of historical uncertainty rather than a single, authoritative interpretation [34].

In addition, branching can be used in a more interactive, *graphical-adventure* mode, akin to the *Monkey Island* saga, where the user is invited to choose between competing reconstructions. This might include the deliberate inclusion of *implausible* or even absurd options that, when selected, trigger explanatory feedback: why a given sequence conflicts with the material record, spatial constraints, or ritual practice. In this way, branching supports not only academic comparison but also public-oriented interpretation by making plausibility criteria explicit and pedagogically accessible.

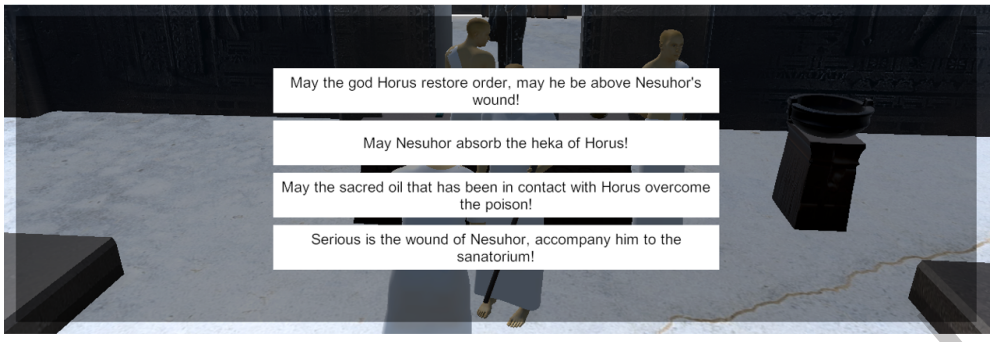


Fig. 11. The dynamic selection panel for branching ritual pathways (Methods a-d).

5.4 The 3D Simulation as a Refinement Tool

Beyond its value as an immersive presentation, the simulation functions as a practical research tool for *specifying* a ritual in operational terms. When a ritual description is encoded as data (characters, artifacts, places, and a time-ordered play of actions), the executable becomes a testbed that exposes mismatches between the authored definition and the instantiated 3D scene. Importantly, the issues discussed below are not treated as evidence against a historical hypothesis; rather, they are treated as actionable diagnostics of the *formal ritual specification* i.e., whether the current configuration of actors, objects, anchors, and timings yields the intended choreographic and interaction outcome.

In this context, the system supports a rapid iterative loop: the Egyptologist modifies the ritual workbook, relaunches the Unity application, and immediately observes the effects of the change. This tight cycle makes it possible to refine the ritual definition by correcting asset placement, revising anchor points, adjusting step ordering, or updating interaction parameters until the simulation behaves consistently with the intended sequence.

During testing, three recurring classes of discrepancies proved particularly informative for improving the ritual specification:

- **Spatial misconfiguration and placement errors:** Collision detection and proximity checks frequently revealed that certain authored paths or anchor placements caused avatars or props to intersect with static geometry (e.g., the altar). In practice, these outcomes usually stemmed from the imprecise placement of Places (anchors), incorrect object pivots, or inconsistent scales across imported assets, rather than from the implausibility of the ritual itself. The correction typically consisted of adjusting the anchor coordinates in the workbook, refining object transforms (scale/rotation), or selecting alternative anchors that preserve clearances while maintaining the intended staging.
- **Timing and interaction alignment issues:** Because characters and object interactions are assembled from independently recorded motion-capture clips, small timing offsets can produce visibly incorrect contact events, e.g., a pouring gesture that misses its intended target, or a handover that does not coincide with the recipient's grasp. These cases highlight gaps in the authored temporal specification (durations, start positions, or the sequencing of steps) and are resolved through iterative adjustments to step timing and/or the parameters that define prop attachment and release.
- **Visibility and occlusion in the staged scene:** The runtime camera logic can reveal that certain artifact placements or avatar orientations reduce the visibility of key actions from the intended viewpoint. Here, the diagnostic is an indication that the current authored configuration does not communicate the action effectively in the simulation. The remedy is to revise object placement anchors or define alternative camera targets for specific steps so that crucial actions remain visible.

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Fig. 12. Examples of visual issues that require iteration on the ritual definition: a character is going through the altar (*left*); misconfiguration during a drinking sequence (*middle*); and misalignment between characters' animations (*right*).

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5.5 Limitations

The primary limitation of the current system is the reliance on isolated motion capture data and the subsequent complexity of post-processing synchronization. While the synchronization loader mitigated many of these issues by adjusting playback speeds and remapping keyframes, it was unable to fully resolve discrepancies in character heights and spatial pivots. A second limitation is the authoring burden placed on domain experts. For the egyptologists, producing the spreadsheet specification with the full ritual detail is not straightforward, particularly when precise body movements and fine-grained interactions between actors and ritual objects must be described step by step. This increases the likelihood of errors and might require iterative corrections with the technical team (see Figure 12). Finally, the decision to have the runtime executable load all models declared in the JSON file, while successfully avoiding the need for historians to work inside the Unity Editor, also constrains scene-level tuning. Certain aspects of visual configuration, such as refining lighting setups or adjusting material parameters, become harder to fine-tune outside the Unity editor and may require additional iterations to reach the same level of visual fidelity that would be achievable with direct editor-based iteration.

6 Conclusions and Future Work

The modular, data-driven system presented in this paper successfully enables the reconstruction of ancient Egyptian rituals within an interactive 3D environment. By decoupling ritual structure from software execution, the pipeline allows Egyptologists to formalize complex performative practices through structured data without requiring programming skills. However, the transition from historical research to a detailed format introduced significant complexities that were more challenging than initially anticipated.

A primary conclusion of this work is that, while a spreadsheet-based workflow ensures reusability and scalability, the abstraction of dynamic behaviors into tabular constraints requires a high degree of technical precision. The current implementation highlights that:

- The data-driven approach allows the same codebase to be reused across multiple projects by simply updating the input data, fostering interdisciplinary collaboration.
- Explicitly encoding ritual branching and variability allows the simulation to function as an analytical laboratory for testing expert hypotheses rather than a single authoritative reconstruction.

- The simulation serves as a practical research tool for the ritual definition, enabling rapid iterative refinement of its actors, artifacts, spatial anchors, and timings until the specified performance behaves coherently.

The most significant bottleneck identified in the current pipeline is the creation, definition, and synchronization of character animations. The necessity of managing all animation states, including transitions, playback speeds, and frame-level synchronization via code and data entries rather than visual tools like Unity's Animator Controller proved time-consuming and susceptible to human error. Furthermore, isolated motion capture recordings made it difficult to align character interactions seamlessly within the virtual environment, leading to inconsistent interactions in certain ritual acts.

To address these limitations, future work is focused on several key enhancements. We are currently working on applying motion matching [26, 27] techniques to allow experts to represent character movements and actions through high-level descriptions. This transition aims to eliminate the need for users to manually reference specific animation clips or frame data, allowing the system to dynamically select the most appropriate poses and motions based on the ritual's spatial and narrative context. We also plan to incorporate more advanced methods for handling hand animations during grasping gestures.

The current version of the application allows the ritual to be defined in a spreadsheet that is used to generate the JSON configuration for the simulation. Although historians can describe the ritual steps using this spreadsheet, a more intuitive visual authoring tool is needed to simplify this task. As future work, we plan to develop a visual interface inspired by systems such as Unreal Engine's Blueprint and Node-RED, where complex actions can be created by connecting atomic nodes, which could complement our system. However, these approaches can easily lead to highly complex models that are difficult to edit and scale. Therefore, special attention must be paid to the design of the application, which should provide an intuitive interface that satisfies both scalability and usability requirements while enabling multiple historians to contribute their expertise collaboratively.

Having verified the technical feasibility of the pipeline, we plan two complementary user studies. An *expert-based usability evaluation* (a formal user study with domain experts to evaluate the authoring, design, and editing workflow) to measure the cognitive load, the intuitive nature of the spread-sheet usage and the actual time efficiency, and an *end-user experience study* to assess usability, comprehension, and engagement to measure the effectiveness of the representation.

Beyond the Horus *cippi*, the results of our project have the potential to be extended and applied to other kinds of magical artifacts, such as the so-called *magical ivories* or *apotropaic wands* used to protect pregnant women, mothers, and newborn children. Like the Horus *cippi*, these objects combined powerful imagery, ritual action, and performative *logos* to ward off dangerous forces, using an iconographic repertoire of protective deities, hybrid beings, and controlled representations of threatening animals to create a protective barrier. By adapting our modular system to these artifacts, researchers could represent alternative protective scenarios surrounding childbirth and infancy—including different ritual practitioners and household spaces—to visualize multiple hypotheses regarding how these objects were used to mediate divine power, convey the force of *heka*, and transform domestic environments into spaces of magical safeguarding.

Using the 3D model of a Late Period Horus *cippus* from the Museu Egipci de Barcelona, the research presented in this article includes a crucial applied component. The resulting immersive experience may be employed by this museum to enhance the interpretation of Horus *cippi*, foregrounding their function and their ritual mode of use. According to the principles of New Museology, museums are not static repositories of objects but dynamic institutions that must evolve toward modes of interactive engagement. Their objective should be to promote visitor participation, involvement, and learning, transforming themselves from static exhibition spaces into immersive educational environments [45]. Immersive experiences enrich visitors' engagement with cultural heritage and allow artifacts to be contextualized within their ritual and historical-cultural frameworks. We

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argue that such approaches constitute effective tools for reintroducing the voices of cultures of origin, eliciting emotional responses from museum visitors, and enhancing long-term memory.

The source code is available in this GitHub repository.

Acknoledgements

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References

[1] Sergio Alarcón Robledo. 2025. Entangled Ritual and Architectural Practices at North Saqqara. https://gsas.harvard.edu/person/sergio-alarcon-robledo PhD thesis. Harvard University.

[2] Carlos Andujar, Begoña Cayuela, Immaculada Lorés Otzet, Carles Bosch, Milagros Guardia, and Imanol Munoz-Pandiella. 2026. Revealing the Layers of History: Enriching Medieval Cultural Heritage 4D Models with Interactive Narratives. *J. Comput. Cult. Herit.* 19, 1, Article 5 (Jan. 2026), 22 pages. doi:10.1145/3715157

[3] Nicola Carboni and Livio De Luca. 2016. Towards a conceptual foundation for documenting tangible and intangible elements of a cultural object. *Digital Applications in Archaeology and Cultural Heritage* 3, 4 (2016), 108–116.

[4] Mengyu Chen, Marko Peljhan, and Misha Sra. 2021. Entanglevr: A visual programming interface for virtual reality interactive scene generation. In *Proceedings of the 27th ACM symposium on virtual reality software and technology*. 1–6.

[5] Mengyu Chen, Marko Peljhan, and Misha Sra. 2024. ConnectVR: A Trigger-Action Interface for Creating Agent-based Interactive VR Stories. In *2024 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*. IEEE, 286–297.

[6] Silvana Cincotti. 2013. Les fouilles dans le musée: la collection égyptienne de Turin et le Fonds Rifaud. *Cahiers de Karnak* 14 (2013), 279–285.

[7] R Damaševičius and T Sidekerskienė. 2024. Virtual worlds for learning in metaverse: a narrative review. Sustainability, 16 (5), 2032.

[8] Andrea D'Andrea, G De Francesco, et al. 2008. Standards and guidelines for quality digital cultural three-dimensional content creation. In *Digital Heritage*. 229–233.

[9] H Denard. 2009. The London Charter for the computer-based Visualisation of cultural heritage. Draft 2.1, 7 February 2009.

[10] Anna Foka and Gabriele Griffin. 2024. AI, Cultural Heritage and Bias: Some Key Queries that Arise from the Use of GenAI. doi:10.20944/preprints202409.0384.v1

[11] Annie Gasse. 2004. *Les stèles d'Horus sur les crocodiles.* Catalogue du Musée du Louvre, Département des Antiquités égyptiennes. Réunion des musées nationaux, Paris.

[12] Gabriele Gattiglia. 2025. Managing Artificial Intelligence in Archeology. An overview. *Journal of Cultural Heritage* 71 (2025), 225–233. doi:10.1016/j.culher.2024.11.020

[13] Anindita Ghosh, Noshaba Cheema, Cennet Oguz, Christian Theobalt, and Philipp Slusallek. 2021. Synthesis of compositional animations from textual descriptions. In *Proceedings of the IEEE/CVF international conference on computer vision*. 1396–1406.

[14] Anindita Ghosh, Rishabh Dabral, Vladislav Golyanik, Christian Theobalt, and Philipp Slusallek. 2023. IMoS: Intent-Driven Full-Body Motion Synthesis for Human-Object Interactions. In *Computer Graphics Forum*, Vol. 42. Wiley Online Library, 1–12.

[15] R. Gillam, C. Innes, and J. Jacobson. 2013. Performance and ritual in the virtual Egyptian temple. In *Fusion of Cultures: Proceedings of the 38th Conference on Computer Applications and Quantitative Methods in Archaeology (BAR International Series, Vol. 2494)*, Francisco Contreras, Mercedes Farjas, and Francisco J. Melero (Eds.). Archaeopress, Oxford. Computer Applications in Archaeology (CAA), Granada, Spain, 2010.

[16] Jeffrey Jacobson and Robyn Gillam. 2012. The egyptian oracle; Recreating egyptian religious ceremony in mixed reality. *unpublished.[Online]. Available: http://publicvr. org/publications/JOCCH-7. pdf* (2012).

[17] Konstantina Karterouli and Yota Batsaki. 2021. AI and Cultural Heritage Image Collections: Opportunities and challenges. doi:10.14236/ewic/EVA2021.33

[18] Joshua McCoy, Mike Treanor, Ben Samuel, Noah Wardrip-Fruin, and Michael Mateas. 2011. Comme il faut: A system for authoring playable social models. In *Proceedings of the AAAI conference on artificial intelligence and interactive digital entertainment*, Vol. 7. 158–163.

[19] LL Micoli, G Caruso, and G Guidi. [n. d.]. Design of Digital Interaction for Complex Museum Collections. Multimodal Technologies and Interaction. 2020; 4 (2): 31.

[20] Laura Loredana Micoli, Sara Gonizzi Barsanti, Giandomenico Caruso, and Gabriele Guidi. 2019. Digital Contents for Enhancing the Communication of Museum Exhibition: The Pervival Project. *The International Archives of the Photogrammetry, Remote Sensing and*

Just Accepted

Spatial Information Sciences (2019). https://api.semanticscholar.org/CorpusID:182678057
[21] Microsoft. [n. d.]. TRELLIS: Structured 3D Latents for Scalable and Versatile 3D Generation. https://microsoft.github.io/TRELLIS/. [Software].
[22] Movella. [n. d.]. Xsens MVN Awinda Motion Capture System. https://www.movella.com/motion-capture/xsens-mvn-awinda. [Hardware].
[23] Sander Muenster. 2022. Digital 3D technologies for humanities research and education: an overview. *Applied Sciences* 12, 5 (2022), 2426.
[24] OpenAI. [n. d.]. OpenAI Audio Speech: text-to-speech model tts-1-hd. https://platform.openai.com/docs/guides/speech. [Software].
[25] Dan Pollak, Jonathan Giron, and Doron Friedman. 2023. Inceptor: an open source tool for automated creation of 3D social scenarios. In *2023 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. IEEE, 474–476.
[26] Jose Luis Ponton, Sheldon Andrews, Carlos Andujar, and Nuria Pelechano. 2025. Environment-aware motion matching. *ACM Transactions on Graphics (TOG)* 44, 6 (2025), 1–18.
[27] Jose Luis Ponton, Haoran Yun, Carlos Andujar, and Nuria Pelechano. 2022. Combining motion matching and orientation prediction to animate avatars for consumer-grade VR devices. In *Computer Graphics Forum*, Vol. 41. Wiley Online Library, 107–118.
[28] Rafael Pérez Arroyo. 2001. Ancient Egypt: Music in the Age of Pyramids. [CD].
[29] Simone Restivo, Alberto Cannavò, Davide Mezzino, Roberta Spallone, Fabrizio Lamberti, et al. 2023. Interacting with ancient Egypt remains in high-fidelity virtual reality experiences. In *EUROGRAPHICS Workshop on Graphics and Cultural Heritage*. Eurographics-The European Association for Computer Graphics.
[30] Robert Kriech Ritner. 1989. Horus on the Crocodiles: A Juncture of Religion and Magic. In *Religion and Philosophy in Ancient Egypt*, James P. Allen et alii (Ed.). Number 3 in Yale Egyptological Studies. Yale University, New Haven, Connecticut, 103–116.
[31] Robert Kriech Ritner. 1993. *The Mechanics of Ancient Egyptian Magical Practice*. Studies in Ancient Oriental Civilization, Vol. 54. University of Chicago Press, Chicago.
[32] Rokoko. [n. d.]. Rokoko Blender Plugin. https://www.rokoko.com/integrations/blender. Real-time 3D character animation & retargeting in Blender [Software].
[33] Samuel S Sohn, Danrui Li, Sen Zhang, Che-Jui Chang, and Mubbasir Kapadia. 2024. From words to worlds: Transforming one-line prompt into immersive multi-modal digital stories with communicative llm agent. *arXiv preprint arXiv:2406.10478* (2024).
[34] Roberta Spallone, Fabrizio Lamberti, Davide Calandra, Davide Mezzino, Johannes Auenmüller, and Martina Rinascimento. 2023. Recontextualizing the standing Sekhmet statues in the Temple of Ptah at Karnak through digital reconstruction and VR experience. *DisegnareCON* 16, 31 (2023), 4–1.
[35] Elaine A Sullivan. 2020. *Constructing the sacred: Visibility and ritual landscape at the Egyptian necropolis of Saqqara*. Stanford University Press.
[36] Elaine A Sullivan. 2023. The Senses & the Sacred: A Multisensory and Digital Approach to Examining an Ancient Egyptian Funerary Landscape. In *Capturing the Senses: Digital Methods for Sensory Archaeologies*. Springer International Publishing Cham, 37–61.
[37] Stella Sylaiou and Panagiotis Dafiotis. 2020. Storytelling in virtual museums: engaging a multitude of voices. In *Visual computing for cultural heritage*. Springer, 369–388.
[38] Omid Taheri, Vasileios Choutas, Michael J Black, and Dimitrios Tzionas. 2022. GOAL: Generating 4D whole-body motion for hand-object grasping. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*. 13263–13273.
[39] The Giza Project at Harvard University. 2024. Digital Giza: The Giza Project. http://giza.fas.harvard.edu/.
[40] The Metropolitan Museum of Art. n.d. *Magical Stela with Horus the Child*. The Metropolitan Museum of Art. https://www.metmuseum.org/art/collection/search/546037 The Met Collection, accessed 2026-03-09.
[41] Christophe Thiers and Pierre Zignani. 2011. The temple of Ptah at Karnak. *Egyptian Archaeology* 38 (2011), 20–24.
[42] Núria Torras-Benezet. 2021. The Pure Priest of Sekhmet, Between Health and Disease. In *Pharmacy and Medicine in Ancient Egypt: Proceedings of the Conference Held in Barcelona (2018) (Archaeopress Egyptology, Vol. 34)*, Rosa Dinarès, Mikel Fernàndez, and Maria Rosa Guasch (Eds.). Archaeopress Publishing Ltd, Oxford, 116–124.
[43] Núria Torras-Benezet. 2026 (forthcoming). Magical Artifacts from Ancient Egypt: Tradition, Interculturality, and Survival in the Light of Items from Public and Private Collections in Spain. In *Proceedings of the 13th International Congress of Egyptologists (Leiden 6-11 August 2023). Egyptologische Uitgaven*. Peeters Publishers, Leuven. https://www.academia.edu/106293478/Magical_Artifacts_from_Ancient_Egypt_Tradition_interculturality_and_survival_in_the_light_of_items_from_public_and_private_collections_in_Spain Poster presentation and congress proceedings.
[44] Branislav Ulicny and Daniel Thalmann. 2002. Crowd simulation for virtual heritage. In *Proceedings of first international workshop on 3D virtual heritage*, Vol. 2832.
[45] Peter Vergo. 1989. *The New Museology*. Reaktion Books, London.
[46] D. M. Wheeler. 2023. Egyptian ritual as performance art. Paper presented at the Annual Meeting of the American Research Center in Egypt (ARCE).

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Just Accepted