




# Digging through the Virtual Sand of Time: Development and Evaluation of *Hetepheres Tomb VR*

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## Abstract

Less than 100 meters from the base of the Great Pyramid of Giza lies the tomb of Queen Hetepheres I. 2025 marks the 100th anniversary of its discovery, a milestone that is likely to draw renewed attention to this relatively unknown archaeological site. To share the story of the tomb's excavation and the mysteries surrounding it with a broader audience, we developed the virtual reality experience *Hetepheres Tomb VR*. In this paper, we present the didactic concept behind the experience, along with practical implementation strategies designed to ensure maximum user-friendliness and minimize motion sickness. To evaluate the effectiveness of these design choices, we conducted a user study, the results of which are discussed in detail. These findings also informed subsequent optimizations of the application. With this work, we aim to provide museum-related VR projects - particularly those in the conceptual phase - with insights into our development process. We hope to offer both guidance and inspiration for creating engaging, accessible virtual experiences. *Hetepheres Tomb VR* is currently available for free on Steam and the Meta Quest app store, making it suitable for use in educational settings and museum exhibitions.

## CCS Concepts

• **Applied computing** → *Interactive learning environments; Media arts*; • **Human-centered computing** → *Empirical studies in HCI*;

## 1. Introduction

The three pyramids of the Giza necropolis are among the most iconic monuments of antiquity and have been recognized as a UNESCO World Heritage Site since 1979. The largest of the three, the Pyramid of Khufu, originally stood at 146.59 meters and dominated the surrounding landscape. Already in ancient times, Antipater of Sidon listed it among the Seven Wonders of the Ancient World. As the only one of these wonders still in existence today, it represents the pinnacle of the craftsmanship of ancient Egyptian builders.

However, less than 100 meters from the base of the Great Pyramid lies another archaeological site of significant importance: the tomb of Hetepheres I, mother of Pharaoh Khufu, the builder of the eponymous pyramid. While this tomb remains relatively unknown to the general public, it holds considerable scientific interest - perhaps even rivaling that of the Great Pyramid itself.

Discovered accidentally in February, 1925, the tomb presented a number of archaeological mysteries. Scholars have long explored questions such as why such a prominent individual was buried in an unexpectedly modest and concealed grave, and why the royal alabaster (travertine) sarcophagus found within was empty, despite the presence of mummified viscera in the burial chamber.

To make this knowledge accessible to a broader audience, we de-

veloped a virtual reality (VR) application entitled *Hetepheres Tomb VR – Secrets of the Lost Queen*, which we published on the Meta Quest app store [Dre25c] and on Steam [Dre25c]. This immersive experience enables users to engage with key historical milestones and unanswered questions. In accordance with contemporary recommendations for knowledge transfer in museum contexts [HKK\*20], the experience embeds scientific content in an interactive format. Rather than merely presenting static media such as images, audio guides, and 3D objects, we emphasized interactivity to enhance user motivation. Visitors are invited to take photographs of the digitally reconstructed site, excavate the tomb, and even reconstruct the lost golden throne of Hetepheres I using modern tools.

With the initial version of the VR experience complete, we sought to evaluate whether the concept was suitable for integration into museum exhibitions. Specifically, we investigated its practical applicability in daily museum operations. To this end, we conducted a small-scale user study to explore factors such as average playthrough time, ease of interaction, potential for motion sickness, aspects of the application that were difficult to understand, and how much content users remembered after a single playthrough.

The following section offers an overview of related research on virtual reality in museum didactics that informed our conceptual

and development processes. Section 3 presents the cultural and historical context of the tomb. In Section 4, we describe our didactic design for the VR exhibition, while Section 5 outlines the current implementation. Section 6 details our evaluation process and the data collected, which are analyzed and discussed in Section 7. Finally, Section 8 provides an outlook on future developments and concludes the paper.

## 2. Virtual Reality for Cultural Heritage Preservation

### 2.1. A Brief History of Virtual Reality in the Museum Context

The term Virtual Reality (VR) refers to a reality that is "something in essence or effect, though not in fact; existing virtually though not actually" [Ety]. Berkman [Ber18] provides a historical overview of VR, distinguishing between the more technologically grounded concept introduced by Jaron Lanier in 1987 [Soc17], and earlier literary or science fiction interpretations of the term.

Berkman further explains that in the early days of digital media, PC-based applications - such as 3D models or games - were often labeled as VR. However, with technological advancements, VR today is more narrowly associated with the use of dedicated hardware, particularly head-mounted displays (HMDs). As noted in [HW23], HMD-based VR offers a significantly more immersive experience than PC-based systems, making it particularly suitable for "processes [that] are difficult or impossible to perform in the real world (e.g., taking participants 'back in time')".

The broader term *Extended Reality (XR)* has since emerged, encompassing VR, Augmented Reality (AR), and Mixed Reality (MR). Since the release of the HTC Vive in 2016 - the first consumer-grade HMD system with sensor-based tracking - users have been able to navigate virtual spaces freely ([Bar24]). This technological shift catalyzed the adoption of VR in museums, leading to a growing number of VR-enhanced exhibitions ([Ing22]).

Today, XR technologies are frequently cited as essential tools for modern museum practice [HKK\*20], as they facilitate key aspects of contemporary knowledge dissemination: adapting content to the audience's level, fostering user participation, promoting inclusion and diversity, and increasing outreach through open-source distribution. Especially noteworthy is the interactive potential of XR, which allows users to engage with artifacts in ways not possible in traditional exhibits, e.g. handling, rotating, scaling, and even virtually "throwing" them. This interaction shifts visitors from passive observers to active participants.

### 2.2. VR-Based Exhibitions

One of our initial steps in the conception phase was to identify best practice recommendations and successful examples of VR-based exhibitions. The study by Hwei Teeng Chong et al. [TLR\*21] highlighted the growing significance of VR in cultural heritage over the past decade and offered an overview of current trends in VR usage, which supported our initial orientation during the planning phase.

Instead of focusing on available VR tools first, we prioritized identifying suitable content, as recommended by Chong et al.

[TLR\*21], who argue that "*the cultural heritage content determines the design and development of VR for cultural heritage before integrating it with specified VR tools*". We also aimed to optimize "*VR interactivity [...] to a high level of usability to meet users with low to no experience*."

Additional design strategies were drawn from Rodríguez-García et al. [RGCB24], whose work outlined best practices for VR application development in the heritage sector. For instance, based on their insights, we restricted user movement to three degrees of freedom (3DoF) in certain scenes - e.g., when reconstructing Queen Hetepheres' golden throne - to focus attention on a specific objective. In contrast, we allowed full six degrees of freedom (6DoF) in more explorative scenes.

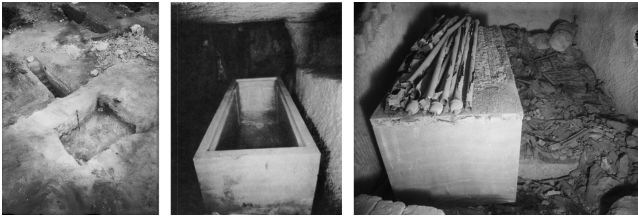
Richardson [Ric24] offers a broader reflection on the significance of VR for museums and presents a list of notable VR exhibitions from recent years. For example, *Van Gogh's Palette* [dOr], hosted at the Musée d'Orsay in late 2023, offered a 10-minute immersive exploration of Van Gogh's techniques and art. Similarly, the Louvre's *Mona Lisa: Beyond the Glass* [Lou21], presented in 2019, allowed visitors to encounter the woman behind da Vinci's painting in a fully immersive 3D environment.

Other significant works in this domain include Cecotti [Cec22] and Theodoropoulos and Antoniou [TA22], who contributed substantially by identifying and analyzing a range of VR applications dedicated to cultural heritage preservation. Among the examples discussed in their studies are *The Dawn of Art* [Atl20], which immerses users in the 36,000-year-old drawings of the Chauvet Cave, and *Nefertari: Journey to Eternity* [Cur18], a 15-minute VR experience that allows users to explore a reconstructed tomb of Queen Nefertari, complete with detailed hieroglyphs and educational content about Egyptian mythology. Both served as key sources of inspiration for our own development process.

### 2.3. Challenges Using VR in Museums

Although VR is still regarded as a novelty and often enhances motivation even in educational settings ([JF24]), it also presents a number of challenges. Shehade and Stylianou-Lambert [SS20] conducted a qualitative study based on interviews with museum professionals, identifying nine categories of limitations: lack of social interaction, staffing and training needs, cost, accessibility, technical difficulties, graphics quality, exhibition flow, distraction, and technology acceptance. To address these issues, we incorporated the study's recommendations into the development of *Hetepheres Tomb VR* and continually revisited them throughout the design process. For example, we prioritized intuitive interaction to reduce the need for staff intervention, thereby lowering staffing and training costs. Additionally, to promote acceptance and minimize hardware requirements, we opted against photorealistic visuals in favor of a stylized, comic-like aesthetic.

Another concern is VR-induced motion sickness, which has been described as a "serious concern that threatens [VR's] success and acceptance" [KG21]. Museum partners emphasized that, within an exhibition context, motion sickness could disrupt visits, particularly for school groups or time-limited tours, and leave a negative impression. We therefore implemented several countermeasures



**Figure 1:** Archival photographs from the excavation documentation: (a) Entrance to the shaft [Ibr25], (b) Photo of the sarcophagus [Rei55], (c) View of the burial chamber [Ibr26]

based on the recommendations of Chang, Kim, and Yoo [CKY20]. These included avoiding automated camera movement (e.g., vehicle travel), limiting abrupt head motion and teleportation, and ensuring high frame rates via optimized, low-polygon 3D assets.

While multiple empirical studies (e.g., [HMEW20], [YX22]) suggest that simulated immersion can enhance learning outcomes compared to traditional methods, cognitive overload remains a key concern. As Sari et al. [csPS\*23] explain, "If [a] stimulus [in the VR] is excessive, it will reduce learning". Following the principles of the Cognitive Theory of Multimedia Learning (CTML) and Cognitive Load Theory (CLT) ([MM02]), we minimized extraneous content. We avoided distracting elements such as animated animals or avatars and used signaling techniques (see [AVS21]) to direct attention to didactic elements - such as highlighting interactive objects with glowing effects - to support focused learning.

### 3. Hetepheres Tomb

The first modern-era glimpse into Queen Hetepheres's subterranean burial chamber, labeled *G 7000 X*, occurred on Saturday evening, March 7, 1925. Located 30 meters (approximately 90 feet) below ground, the small, unfinished chamber contained a large collection of deteriorated furniture, stone vessels, ceramics, inlaid jewelry, an alabaster (travertine) sarcophagus, and many other items. Ironically, George Reisner (1867–1942), director of the *Harvard University - Boston Museum of Fine Arts Expedition*, was not present at the discovery; he was in Boston, teaching at Harvard and serving as curator at the Museum of Fine Arts. The excavation work at the Eastern Cemetery in Giza was supervised by expedition staff Alan Rowe, T.R. Duncan Greenlees, and foreman Said Ahmed Said.

The accidental discovery of the shaft occurred on either February 2 or 9, 1925, when expedition photographer Mohammedani Ibrahim's tripod slipped on "Queens Street," revealing plaster covering and limestone fill blocks beneath - clearly placed to conceal what lay below ([RS],[Reia]). The Arabic expedition diary, kept by Said Ahmed Said, notes on February 9, 1925, a "layer of plaster that was photographed and drawn recently..."

On March 16, 1925, Said Ahmed and Greenlees sealed the entrance to the burial chamber. Then, on April 4, inspector James Quibell relayed that Antiquities Service director Pierre Lacau did not wish the tomb reopened until Reisner could return to Cairo [Ahm]. Reisner departed from New York and arrived in Giza on July 22 [Reib]. Although excavation was scheduled to resume im-

mediately, Reisner fell ill with shingles, delaying progress. Work finally resumed on January 21, 1926, in the burial chamber of *G 7000 X* ([RS55]). Fig. 1 (a) illustrates the shaft and stairs leading to the tomb after first stone removal.

The chamber was found in a devastated state, with many of the grave goods severely damaged by time, as depicted in Fig. 1 (c). The queen's identity was confirmed on April 14, 1926, from inscriptions found on the back of a carrying chair. She was identified as the mother of King Khufu, builder of the nearby Great Pyramid. Once most of the tomb's contents had been removed, an "opening ceremony" was held on March 3, 1927, during which the lid of the royal sarcophagus was lifted - only to reveal that it was empty, as shown in Fig. 1 (b). An alabaster (travertine) canopic chest, typically used to store the internal organs of the deceased, was later discovered in a sealed niche on the eastern wall. Removed on May 23, 1927, it contained organic remains suspended in a natron-based (formaldehyde-like) solution that had remained liquid for over 5,000 years. This was likely all that survived of Queen Hetepheres herself. The sarcophagus was later recovered for further scientific study. For a more comprehensive account of the discovery, see [Man23].

In total, the excavation of Hetepheres's tomb generated 1,701 pages of plans, notes, and drawings, 1,057 glass plate photographs, and required 321 working days. Today, most of the tomb's artifacts are on display at the Grand Egyptian Museum, just north of the Giza Pyramids. Additionally, a substantial collection of digitized documentation is available online via Digital Giza ([Gizb],[Giza]).

### 4. Didactic Concept

Following our initial research into best practices and challenges surrounding didactic virtual reality (VR) experiences, we began developing a didactic concept for *Hetepheres Tomb VR*. In this phase, we collected and categorized available materials related to the tomb based on their potential for educational use. We used the categories: storytelling, visual mediation, auditory mediation, and interactive mediation. The selected materials were then evaluated for their communicability within a VR context - for example, whether a particular narrative element would be more effective if conveyed through text alone or supplemented with audio guidance. In particular, the interactive mediation focused on translating physical, haptic activities into virtual interactions - such as digging in the sand or reconstructing an ancient chair from the tomb.

Based on the selected materials and their respective modes of communication, we defined three main didactic objectives for *Hetepheres Tomb VR*: (D-I) *Players experience the discovery and excavation of the tomb first-hand*, (D-II) *Players gain insight into the modern technologies and methods used by the Harvard Museum of the Ancient Near East to reconstruct the lost golden chair of Queen Hetepheres* [Man17], and (D-III) *Players receive an exhibition-like presentation of scientific material related to the tomb*.

To achieve (D-I), we designed an interactive, storytelling-driven experience in which players explore the Egyptian landscape and perform the manual labor required to uncover and examine the tomb. A narrator accompanies the experience, guiding players through the historical events of 1925/26.

For (D-II), we implemented an interactive laboratory in which players virtually reenact the reconstruction of Queen Hetepheres’s golden throne. To reflect contemporary archaeological methods, the lab incorporates modern technologies such as a CNC milling machine. A video of the reconstruction process is available at [otAnc16], and the original 3D model used is illustrated in Figure 2 (a) and accessible via [pma23].

To address (D-III), we created a digital museum featuring interactive display cases. These showcases contain various exhibits - such as photographs from the excavation and 3D models of artifacts - that can be picked up, scaled, and examined. Each exhibit includes additional, text-based information to support knowledge acquisition.

## 5. Implementation

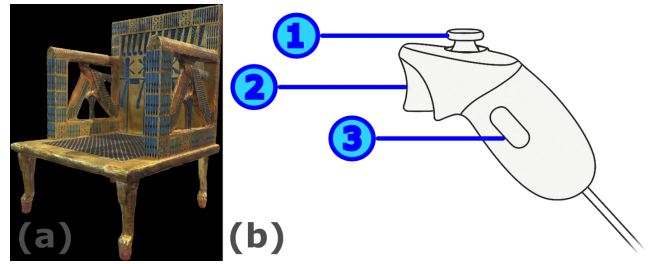
Based on the didactic goals presented in Section 4, *Hetepheres Tomb VR* was developed using the Unity Game Engine [Uni25], with the ExPresS XR framework [Dre25a] supporting the virtual reality components. We chose the Meta Quest 3 headset as our primary target platform, as we had extensive experience with it from prior projects. In our experience, museums often favor this headset (or its predecessor, the Meta Quest 2) due to its balance of affordability and technical capability [Rid25]. However, because ExPresS XR is based on the OpenXR standard [Khr25], the application can be easily adapted to other VR platforms. In addition to the Meta Quest 2 and 3, we also successfully ported the application to the HTC Vive Pro 2 and the PICO 4.

### 5.1. Modelling

Because large parts of the Giza Necropolis are still intact today, environmental landmarks were reconstructed using available 3D scans derived from photogrammetry of drone footage and satellite imagery. For example, a 3D reconstruction of the Giza Plateau available on Sketchfab [pie21] served as a key reference. However, due to the high altitude of most footage, the resulting models lacked detail and were unsuitable for close-up presentation in VR.

To obtain more detailed models, we captured closer-range data using the Polycam smartphone app [Pol25]. This allowed us to create detailed models of Queen Hetepheres’s sarcophagus and canopic chest, which players can inspect closely in VR. While the raw scans were visually rich, they were typically too complex for real-time rendering. Using the open-source 3D modeling software Blender [Ble25], we recreated these artifacts as simplified models. We then projected high-quality textures from the original scans onto the simplified geometry, achieving visual fidelity with optimal performance. This process also allowed us to correct scanning artifacts and discolorations.

In addition, we integrated existing models from the Digital Giza Project [Giza], including reconstructions of the tomb structure and various restored artifacts. Other elements, such as the pulley system, restoration tools, and museum display equipment required custom modeling and animation. To ensure historical accuracy, we consulted the digital library of original excavation photographs.



**Figure 2:** (a) 3D model used for the reconstruction of the golden chair [pma23]; (b) Meta Quest 3 controller, used as a reference for interaction design. The following buttons are utilized in *Hetepheres Tomb VR*: (1) Joystick, (2) Trigger button, (3) Grip button.

### 5.2. User Interaction

The interaction design was based primarily on the Meta Quest 3 controllers, which were used in the majority of our testing. While other VR headsets use similar controller layouts, the following descriptions and button names refer specifically to the Meta Quest 3.

As illustrated in Figure 2, user interaction includes teleportation-based movement, object grabbing, button pressing, and trigger-based UI selection. Teleportation is initiated by pressing the joystick upward, projecting an arced beam from the user’s virtual hand. A circular marker indicates the target location, turning green if teleportation is possible, and red if not. When the joystick is released, the player is teleported to the indicated circular marker.

To grab objects, users move their virtual hand into contact with the item and press the grip button. A hand animation illustrates the grasping motion. While holding an object, rotating the controller rotates the object, and the joystick can be used to scale it - upwards to enlarge, downwards to shrink. This is especially useful for smaller items like coins or fragments.

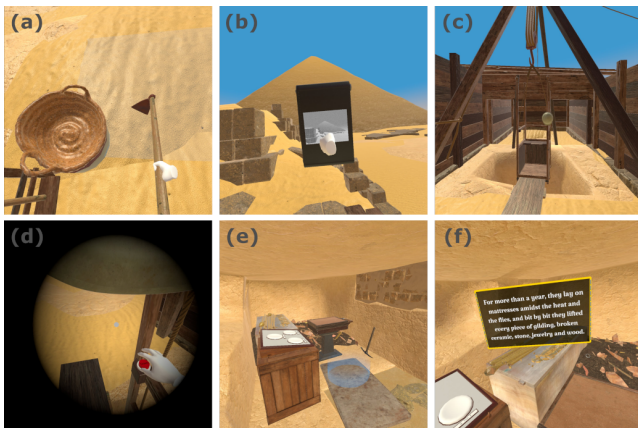
Interaction buttons embedded in the scene are activated by hand contact and serve multiple functions, such as starting audio guides, animating objects, or advancing the narrative. Trigger-based interaction is reserved for user interface elements like the main menu. In such cases, a laser pointer appears from the virtual hand, and UI elements are selected with the trigger button. Because this interaction style reduces immersion, it is used sparingly.

### 5.3. One Playthrough

#### 5.3.1. Experiencing the Excavation

To fulfill didactic goal (D-I), we designed an immersive sequence that allows players to re-experience the discovery and excavation of the tomb. Selected scenes from the experience are shown in Figure 3.

The sequence begins in 1925, as players encounter Mohammedani Ibrahim’s camera already positioned in the Egyptian desert. Then, the tripod collapses, and a stream of sand reveals a hidden shaft beneath, while a narrator explains the historical context. To ease users into the VR experience and reduce cognitive load, this introductory scene is non-interactive.



**Figure 3:** In-game excavation scenes: (a) Shaft digging, (b) Excavation documentation, (c) Shaft entrance, (d) Field-of-view reduction during elevator ride, (e) Signaling, (f) Inside the tomb.

In the following scene, players actively participate in the excavation (Figure 3 (a)). Guided by narration, they replicate early digging procedures: using a rake to uncover the entrance shaft, filling baskets with sand, and loading a trolley for removal. Though the physical exertion is simulated, the environment conveys the intense manual labor under harsh Egyptian conditions. To simplify gameplay and minimize visual clutter, sand is not rendered with full physical realism; instead, simulated transfers are triggered when the rake, basket, and trolley overlap.

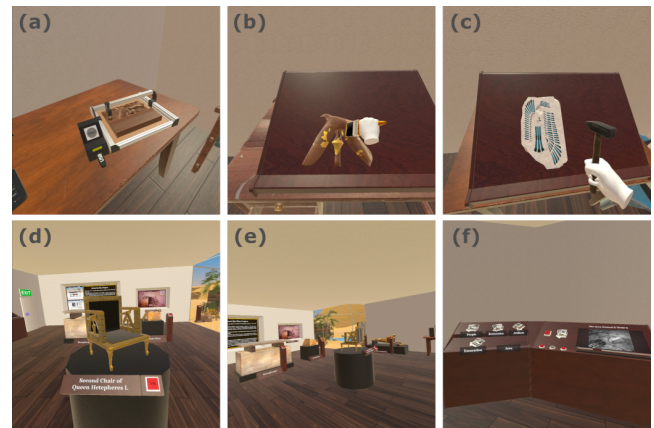
Next, players learn about the meticulous documentation of the excavation (Figure 3 (b)). They replicate this by climbing a scaffold to take a documentary photograph from above. After completing this task, players begin their descent into the tomb via an elevator (Figure 3 (c)). To reduce potential motion sickness during the 26-meter elevator ride, we applied a field-of-view reduction technique inspired by [FF16] (Figure 3 (d)). This approach has been shown in research to alleviate discomfort [ANMF20; AAMF19; CN19].

Upon reaching the burial chamber (Figure 3 (e)), glowing visual cues guide players through the scene. Inside, they learn about the devastated state of the tomb, the reconstruction of artifacts, and participate in key archaeological moments (Figure 3 (f)). These include opening the sarcophagus - revealing it to be empty - and uncovering the hidden canopic chest by breaking through a plastered niche. Finally, players use a hand-operated winch to carefully retrieve the sarcophagus from the tomb.

### 5.3.2. Reconstruction of the Golden Throne

After completing the excavation, players are teleported into a laboratory that addresses didactic goal (D-II): reconstructing the golden throne of Queen Hetepheres. This scene is depicted in the top row of Figure 4.

Here, the narrator explains the scientific challenges related to the missing throne and the reconstruction strategies used in 2016. Step-by-step, players follow this process. They begin by transferring a 3D model from a PC to a CNC milling machine using a virtual USB stick. The machine then carves the elaborate Horus falcon



**Figure 4:** In-game laboratory and exhibition scenes: (a) CNC carving of the Horus falcon arm elements, (b) Application of gold foil, (c) Breaking out faience inlays, (d) Assembled throne in the virtual museum, (e) Excerpt from the virtual exhibition, (f) Slideshow providing additional information.

arm elements, including numerous cut-out areas within the feathers to accommodate the faience inlays (Figure 4 (a)). Next, players apply a layer of gold foil (Figure 4 (b)) and produce ceramic faience elements by mixing raw materials with colored pigments and firing them in a virtual kiln. Afterward, they break out the fired pieces (Figure 4 (c)) and attach them to the previously milled Horus falcon ornament. Once completed, players then assemble all throne components to form the reconstructed chair. Once assembled, the throne is transferred to the exhibition space.

### 5.3.3. Virtual Exhibition

The final part of the experience addresses didactic goal (D-III): presenting scientific material in a virtual museum. This segment is shown in the bottom row of Figure 4.

Upon placing the throne in its showcase (Figure 4 (d)), players gain access to the broader VR exhibition (Figure 4 (e)). It features interactive exhibits, including the carrying chair, sarcophagus, and canopic chest. Information buttons reveal additional context in the form of text, distinguishing this part of the experience from the audio-guided narration used earlier.

An opening in the exhibition wall leads into a desert oasis, where players encounter objects in their historical context, accompanied by explanatory information buttons. A final section contains a slideshow viewer, showing archival photographs from the excavation site and its findings, each accompanied by explanatory text (Figure 4 (f)). The virtual exhibition also serves as a reflective conclusion, allowing players to revisit the core concepts and finish the experience at their own pace.

## 6. Evaluation

### 6.1. Expert Interviews

To determine which aspects of *Hetepheres Tomb VR* should be evaluated for use in a museum context, we conducted interviews

with three curators from regional museums in southern Baden-Württemberg who had expressed interest in including the application in upcoming exhibitions. Although this number is too small to derive generalizable conclusions, we clustered their responses to identify recurring themes as a foundation for designing our evaluation.

The feedback we received from the curators largely aligned with the findings of Shehade et al. [SS20]. Three main requirements for the VR experience emerged: (1) ease of use, (2) appropriate playtime duration, and (3) effective mitigation of motion sickness. Additionally, several optional features were mentioned as beneficial, including (4) the ability to stream gameplay, (5) multiplayer functionality, and (6) opportunities for active user participation. We summarize these areas of feedback in more detail below.

All three curators had previous experience with VR-supported exhibitions and reported using different types of applications - ranging from digital replicas of physical exhibitions (e.g., on Roman contorniates), to interactive 3D reconstructions (e.g., of the Herodian Temple), and more playful experiences (e.g., a VR demonstration of the Japanese horseback archery sport Yabusame). Regarding (1), the curators noted that complex user interactions tend to require more assistance from staff. For instance, in an exhibition on contorniates, visitors were required to pick up fallen virtual objects - something older audiences found frustrating due to the challenge of balancing the VR headset and controllers while bending down. All curators emphasized that the application should be as intuitive as possible, given the diversity of audiences. For this reason, all three curators planned to provide additional staff support for walk-in visitors over the course of the exhibition.

With respect to (2), expectations for playtime ranged from 10 to 20 minutes, particularly during regular opening hours when spontaneous visits were expected. However, curators noted that actual user engagement time is highly variable: while some visitors want to explore as long as possible, others disengage shortly after putting on the headset. A consensus emerged that 15 minutes of gameplay would likely strike a good balance for most visitors. One curator noted an exception: in school group settings with 20 and more students and a limited time frame (mostly 60–90 minutes), one-to-one supervision is not feasible. In these cases, intuitive controls and adjustable experience duration were considered critical so that each student could try the application.

Regarding (3), all curators agreed - unsurprisingly - that motion sickness must be avoided at all costs. As one curator explained in the context of planned school visits: *"It would be a disaster if half the students ended up on the floor after their VR experience and couldn't attend the rest of the excursion"*.

Two curators emphasized from past experiences the value of being able to stream the user's gameplay to a screen in the exhibition space (4). This feature not only allowed staff to better assist users based on their view, but also had a positive impact on subsequent visitors, who became familiar with the controls by watching others. Moreover, waiting times were perceived as more enjoyable, as visitors often joked about the actions being performed on screen. Since this functionality is typically provided by the operating system of most modern headsets, we did not implement a dedicated in-game solution.

One curator suggested that a multiplayer-enhanced version would be useful for guided group tours (5), allowing a staff member to join users inside the VR experience. However, as this feature was not part of the initial development scope of *Hetepheres Tomb VR* and would require substantial resources, it was not implemented. The same curator also proposed an interaction feature that would allow users to leave something behind within the virtual exhibition (6). To address this request, we considered offering a web interface for the in-game photography feature, allowing visitors' "documentary" images to be saved to the museum's server and integrated into third-party applications.

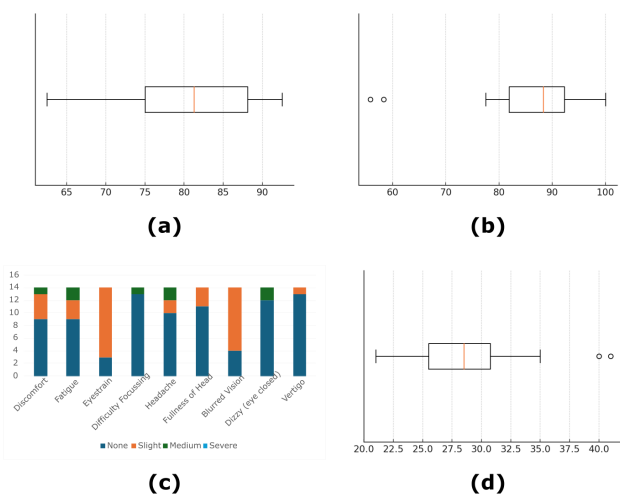
## 6.2. Research Questions and Hypotheses

"Based on the curators' feedback, we derived a set of research questions and hypotheses to guide our evaluation of *Hetepheres Tomb VR*. One key aspect was the duration of a typical playthrough, which ideally should fit within the 15–20 minute timeframe suggested for use in museum settings. This led to our first hypothesis (H1): *One playthrough of Hetepheres Tomb VR requires less than 20 minutes on average*. To assess usability, we formulated two related hypotheses: (H2) *The interactions within Hetepheres Tomb VR are intuitive*, and (H3) *Players require only minimal assistance during their playtime*. Given the importance of user comfort, especially in a museum environment, we also sought to examine the risk of motion sickness. This resulted in hypothesis (H4): *Players do not suffer from motion sickness while using Hetepheres Tomb VR*. Finally, to evaluate the application's educational impact, we proposed (H5): *Players remember information from the excavation process, the reconstruction of the chair, and the final exhibition*".

## 6.3. Methodology

To collect quantitative data, we designed a questionnaire with four sections. The first section consisted of the complete System Usability Scale (SUS) questionnaire [Bro95], which is used to determine a comparable usability score. Additionally, we included an open-text field where participants could report which interactions they found unclear or difficult. The second section addressed motion sickness using 4-point Likert scale questions for the nine symptoms identified in the Virtual Reality Sickness Questionnaire (VRSQ) by Kim et al. [KPCC18]. Again, using an open-text field, participants could describe any specific events or actions that triggered discomfort during gameplay. The third section aimed to assess what participants could recall from a single playthrough. For this purpose, we provided a large free-text area in which they were asked to write down everything they remembered, in as much detail as possible. The fourth and final section of the questionnaire gathered demographic information (e.g., age), along with 5-point Likert scale questions regarding participants' familiarity with VR, interest in museum exhibitions and ancient Egyptian history, and prior knowledge of Queen Hetepheres's tomb. Free-text fields invited participants to share additional feedback or suggestions for improvement.

The following outlines the evaluation procedure used in our study. Participants first received an illustrated guide to the VR interaction techniques. They then entered the application using a



**Figure 5:** Statistical Overview: (a) SUS scores, (b) Inverted VRSQ scores (0 = severe symptoms, 100 = no symptoms), (c) Reported VRSQ symptoms by severity, (d) Playthrough duration in minutes.

Meta Quest 3 headset. We recorded the start and end time of each playthrough and logged support interventions, including a timestamp and short description. Upon completing the VR experience, participants were asked to complete a questionnaire.

## 6.4. Data Collected

### 6.4.1. Statistical Data

We collected responses from 14 participants, aged 17 to 61 ( $M = 30.2$ ,  $SD = 12.2$ ,  $skew = 1.3$ ). On a scale from 1 (no VR experience) to 5 (expert), most rated themselves as moderately experienced ( $M = 3.1$ ,  $SD = 1.1$ ,  $skew = -0.9$ ). Only two participants reported no prior VR experience. Interest in museums was high ( $M = 4.0$ ,  $SD = 0.5$ ,  $skew = 0$ ), with all ratings above 3. Interest in ancient Egyptian history was also relatively strong ( $M = 3.7$ ,  $SD = 1.0$ ,  $skew = -0.2$ ). None of the participants had prior knowledge of Queen Hetepheres's tomb.

The calculated SUS scores (Fig. 5 (a)) ranged from 62.5 to 92.5 ( $M = 78.4$ ,  $SD = 10.9$ ,  $skew = -0.5$ ). VRSQ scores (Fig. 5 (b)) ranged from 55 to 100 ( $M = 85.0$ ,  $SD = 13.3$ ,  $skew = -1.3$ ), with symptoms such as general discomfort (slight: 4, moderate: 1), fatigue (slight: 3, moderate: 2), eyestrain (slight: 11), headache (slight: 2, moderate: 2), and blurred vision (slight: 10) being most common. A detailed breakdown of reported symptoms by severity is shown in Fig. 5 (c). Only two participants reported moderate symptoms of dizziness and one of slight vertigo. The two participants reporting no symptoms rated themselves as VR experts.

Playtimes ranged from 21 to 41 minutes ( $M = 29.2$ ,  $SD = 6.0$ ,  $skew = 0.8$ ) (Fig. 5 (d)). Only three participants exceeded 35 minutes, with the majority (9) completing the experience in 21–30 minutes. Most support requests occurred within the first 10 minutes of gameplay. Five participants struggled with teleportation despite the briefing. Seven encountered difficulties transferring sand from

the rake to the basket. However, all succeeded in transferring it to the trolley without further assistance. The ladder-climbing segment was notably problematic: 11 participants required help understanding how to teleport from the top rung. Six reported "falling between the ladder and the ground", causing confusion. All were eventually able to continue with support. In the tomb, seven participants asked how to open the sarcophagus, which required an unfamiliar pushing motion. Two overlooked the pickaxe needed to access the canopic chest.

In the two sections following the story-based excavation, there were hardly any support requests from participants. In the laboratory setting, one participant was unsure whether a delay during clay firing was normal. In the museum section, four participants experienced toggling issues with information buttons, unintentionally opening and closing info panels multiple times.

Overall user satisfaction was rated highly on a 1 (excellent) to 5 (poor) scale ( $M = 1.4$ ,  $SD = 0.8$ ,  $skew = 1.5$ ).

### 6.4.2. Freeform Feedback

In the open-text responses, eight participants described difficulty understanding how to transfer sand from the rake to the basket — confirming earlier observational data. Eleven reported problems climbing the ladder, and five described the experience of "falling" as disorienting. The latter recommended a bypass option. Three participants misunderstood how to submit the documentary photo after taking it with the trigger button, expecting it to be submitted again using a controller button rather than interacting with an in-game object.

Seven participants reported dizziness during the elevator ride and suggested an option to skip this sequence. Inside the tomb, four struggled to open the sarcophagus and one had trouble locating the niche. Five reported issues with exhibition info buttons, which triggered multiple toggles when pressed too quickly.

All participants provided written reflections on what they remembered from their playthroughs. Following Mayring and Fenzl's methodology for qualitative content analysis [MF19], we categorized their responses. All participants identified the three main phases: excavation, laboratory, and exhibition. However, the level of detail varied significantly. Common themes included the name of Queen Hetepheres and her relation to Pharaoh Khufu, the excavation documentation, the condition of the tomb, the empty sarcophagus, and the throne reconstruction. Specific names, functions of artifacts, or detailed context were rarely recalled.

## 7. Discussion

Although we had only 14 participants in our study, the results provided valuable insights into the research hypotheses outlined earlier. First, hypothesis (H1) - that a single playthrough of *Hetepheres Tomb VR* would require less than 20 minutes - was not supported. The reported playtimes included the time required to resolve technical support requests, which we chose not to exclude, as such interactions are also part of real-world exhibition use. With an average duration of approximately 30 minutes and moderate standard deviation, the experience took significantly longer than initially expected. This finding has implications for use in museums, where

fewer visitors can complete the experience within a given time-frame. Although we observed that some test subjects read the information carefully and interacted extensively with the environment, it would be unrealistic to assume that museum visitors will proceed through the VR exhibition in 'speedrun' mode. As a result, we implemented a feature that allows direct access to the beginning of each of the three experience segments described in 5.3. This enables museum staff to dynamically adapt the VR visit to suit audience flow: visitors can either play through the entire experience or focus on one segment based on their interest and time availability. Alternatively, multiple VR stations could be set up, each linked to a corresponding real-world exhibit and dedicated to just one part of the experience.

While the average SUS score of 78.4 alone lacks strong interpretive value in the absence of a direct comparison version of *Hetepheres Tomb VR*, it still provides a general sense of perceived usability. According to Lewis and Sauro [LS16], SUS scores below 68 are considered below average, while scores above that threshold are considered above average. Bangor et al. [BAK\*08] classify scores above 71.1 as "acceptable", and those below 51.6 as "unacceptable". In a more nuanced scale, Bangor et al. [BKM09] describe scores above 80.8 as "excellent", while scores between 71.1 and 80.8 are "good". Thus, the SUS score in our study places the current version of *Hetepheres Tomb VR* in the range of "good" supporting hypothesis (H2).

Observational data also support hypothesis (H3): most support requests occurred within the first 10 minutes of gameplay. This suggests that multiple VR stations could be supervised by a single staff member. Based on both our observations and the participants' textual feedback, we implemented several adjustments: in-game animations were added to the introduction scene to better explain teleportation, and similar animations were added to explain the sand-passing mechanic. While these additions reduce immersion slightly, they are expected to prevent confusion and improve usability. Regarding the problematic ladder sequence, we implemented a bypass button, which also serves to mitigate potential motion sickness. We decided against changing the photograph-taking process to avoid overloading the controller with too many input mappings. For the sarcophagus scene, we added a subtle visual cue - a directional arrow - to indicate how the lid must be moved. For the toggling issue in the exhibition, we added a cooldown to the button interaction to prevent rapid, unintended switching.

The average VRSQ score of 15.0 also requires contextual interpretation. Since we could not identify a standardized adjectival scale for interpreting raw VRSQ results, we referred to the reliability classification framework proposed by Ursachi et al. [UHZ15], which defines scores between 0.8 and 0.95 as "very good". However, because the VRSQ measures symptom severity - where higher values indicate greater discomfort - we inverted the score (by subtracting it from 100) to align it with this positive reliability scale. This resulted in a transformed score of 85.0, which falls within the "very good" category. Although Ursachi et al. consider scores above 0.95 to be suspiciously high, potentially indicating redundancy [HNC01], our result remains within an acceptable range. It is worth noting, however, that two symptom-free participants self-identified as VR experts, and the overall sample was relatively

young - factors that likely skewed the result positively. Even when removing the two outliers, the adjusted score remained high at 82.5, still within the "very good" range. Additionally, many participants reported 'softer symptoms' such as eyestrain, fatigue, and blurred vision, which may have been caused by the longer-than-expected usage time with the headset, leading to strain in the head and eye area. We therefore cautiously conclude that hypothesis (H4) is supported. Nevertheless, we acknowledge that average scores may not fully capture individual variability. To further reduce potential discomfort, we added bypass options for both the elevator ride and the ladder climb.

Regarding the educational goal, feedback supporting hypothesis (H5) was limited in detail. While all participants remembered the three major segments - excavation, laboratory, and exhibition - most only recalled one or two specific details. Still, the most frequently remembered aspects included: the name of Queen Hetepheres and her relationship to Pharaoh Khufu, the documentation process during excavation, the condition of the tomb upon discovery, the empty sarcophagus, and the throne reconstruction. Although fewer participants remembered finer details (e.g., names of the excavation team or exhibit functions), we believe that in the museum context, this level of retention is acceptable. It may serve to raise awareness about the tomb of Queen Hetepheres, and for visitors with a deeper interest in ancient Egypt (as many of our participants reported), it could inspire further exploration beyond the VR experience. Therefore, we cautiously assume that the three didactic objectives (D-I), (D-II), and (D-III), introduced in Chapter 4, were at least partially achieved in *Hetepheres Tomb VR*, as participants were able to recall the core narrative and basic information about the tomb. However, further evaluation is needed to assess deeper learning outcomes.

## 8. Conclusion & Outlook

Designing a VR experience for the museum context is a challenging task, as it requires a well-thought-out didactic concept, intuitive interaction design, motion sickness prevention, and immersive storytelling. The goal is to engage visitors, ensure high user acceptance, and facilitate knowledge transfer at the same time.

In this paper, we have presented our contribution to this field by outlining the development of *Hetepheres Tomb VR*: a virtual reality experience that transports users back to the excavation of burial chamber G 7000 X - less prominent in public awareness than the nearby Great Pyramid - and the final resting place of Queen Hetepheres I, mother of Pharaoh Khufu. We described the historical and cultural background of the tomb, our didactic concept, and the design considerations that guided the technical implementation.

To assess the feasibility of using the application in a museum setting, we conducted an end-user evaluation focused on usability, motion sickness, and learning outcomes. The findings helped us identify strengths and weaknesses of the initial implementation. Based on the results, we carried out a series of optimizations to improve usability and reduce the need for staff support. We also introduced bypass options to further mitigate motion sickness triggers. *Hetepheres Tomb VR* is now publicly available on Steam [Dre25c] and the Meta Quest Store [Dre25b], allowing for free use in both personal and educational contexts.

In summer 2025, the application will be featured in an exhibition at the Museum of the Ancient Cultures (MUT) in Tübingen, in cooperation with the Egyptian collection. In addition, initial plans are underway to use the VR application during special events at the Harvard Museum of the Ancient Near East, as well as in academic teaching within the Department of Anthropology and the Department of Near Eastern Languages and Civilizations at Harvard University. These exhibitions and teaching contexts will provide valuable opportunities to conduct further user testing and assess whether the implemented optimizations have achieved the desired improvements.

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