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The Secret of Bastet: Integrating VR and 3D Printing for the Study and Exhibition of a Cat Mummy

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Abstract

This paper presents the design and evaluation of a twofold dissemination experience to enhance the scientific study of a cat mummy. The mummy is part of the archaeological collection of an art museum. It has undergone scientific analysis, resulting in a large amount of digital data collected via X-ray, CT and photogrammetry, leading to significant discoveries about the nature and history of the mummy.
The first part of the dissemination approach resulted in the production of a 1:1 scale transparent copy, which gives visitors a clear view of the mummy's contents. It has joined the museum's collection and is now displayed alongside the original mummy. The object is both aesthetic and scientific. It was produced using an advanced 3D printing technique based on 3D data generated from segmentations of CT scan data.
The second part consists of a VR-based experience proposed to the museum's visitors, highlighting the scientific process that has led to new knowledge and unresolved questions.
The VR environment guides users through data production, exploration and analysis, enhancing interpretation.
This VR experience was first showcased at an international XR event, and later at the museum's weekly events. Two user studies were conducted on these occasions, using subjective questionnaires to gather feedback. The first assessed the presence, usability and comfort of the VR experience. The second assessed the impact on dissemination. The results show a strong user interest in the scientific approach and confirm the public interest in this method. The experience is now routinely offered in the museum.

CCS Concepts
• ***Human-centered computing*** → ***Virtual reality;*** • ***Applied computing*** → *Fine arts;* ***Interactive learning environments;***

1. Introduction

In recent years, the fields of digital heritage and cultural preservation have increasingly embraced innovative technologies such as virtual reality (VR) and 3D printing. These advancements offer opportunities to explore and interact with historical artifacts and sites, enabling immersive experiences that enhance public engagement and education [LJtDC20]. VR allows users to navigate and visualize complex structures and objects in a three-dimensional space, while 3D printing facilitates the creation of tangible replicas, making cultural heritage more accessible [SRH*20].

The presented work details the design and evaluation of a twofold dissemination project, aiming at advancing the scientific study of a cat mummy. This project is grounded in the archaeological collection of a museum a fine arts. The original study was initiated following a comprehensive study by the University of Manchester on approximately 800 animal mummies, revealing that about one-third were empty [MAD11]. The study uncovered various insights about the cat mummy and generated extensive digital data through X-ray, computed tomography (CT), and photogrammetry.

We have explored the combined use of a 3D printed replica of this museum artifact alongside a VR experience to improve its scientific study and enhance visitor engagement and create an immersive educational experience in the museum. The 3D printed copy was based on CT scan data and produced in collaboration with a private company specialized in industrial additive manufacturing. The VR application was created through an interdisciplinary collaboration involving the museum team, a computer science laboratory, an archaeology laboratory, a VR research team from a private company, and a graphics studio. The experience guides users through the production, exploration, and analysis of the data, aiding in the interpretation by identifying and counting cat bones.

An original and innovative aspect of this work lies in the VR

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application, which invites visitors to engage in a form of scientific role-playing, adopting the perspective of a researcher to explore and analyze archaeological data. This approach opens up new perspectives for science communication by fostering active participation in the process of scientific interpretation.

By integrating these two approaches, we aimed at providing a richer and more interactive understanding of cultural heritage, allowing users to explore not only the physical replica but also to immerse themselves in a Virtual Environment (VE) that simulates the historical and scientific context of the object.

Following its initial presentation at an international professional event in 2023, the VR experience was showcased at the museum during weekly dissemination events. Two user studies were conducted to gather and analyze feedback via subjective questionnaires. The first study was intended to assess the quality of the VR experience in terms of presence, usability, and comfort. The second study aimed at evaluating the impact of the dissemination experience on the visitors of the museum. In addition, several other outcomes of the project, intended more for the scientific study process, have been showcased to museum visitors at various cultural events, based on either 3D printing, VR and AR applications. Regarding The 3D printed copy of the mummy, it joined the real mummy in the archaeological part of the fine art museum, and is now permanently part of the exhibition.

2. Related works

This section presents an overview of existing work on the application of digital technologies, in particular 3D printing and extended reality (XR), in the field of cultural heritage and museums, with a specific focus on Egyptology and the study of mummies.

2.1. The rise of XR in museums

Virtual reality (VR) and augmented reality (AR) are increasingly being adopted by museums to provide immersive experiences that enrich public engagement and education. VR allows users to navigate and visualise complex objects and structures in three-dimensional space, while AR superimposes digital information on the real world, encouraging interaction between virtual and physical elements. These technologies are in use for remote visits, an area of particular interest in the aftermath of the COVID-19 pandemic [GB22], the reconstruction and visualisation of artefacts [GSN*18, Vis23] and environments [BBDS*10], and to increase visitor engagement and education through gamification or the recreation of historical contexts [RBO*21, PPM*20]. Studies are also looking at the UX design and evaluation of XR experiences in museums, identifying different types of museum experience (objective, cognitive, introspective, social) and proposing categories of mixed reality experience (exploration, extended scale, knowledge, restoration, encounter, sharing) [YK21]. The project presented combines exploration and knowledge experiences, enriched by the simulation of the scientific analysis process. This approach complements existing educational uses of VR in museums, which propose to apply multimedia learning theory and emotional design to enhance motivation and conceptual understanding [ZCW22, May20]. In our case, we aim to stimulate cognitive engagement through investigative role-play, encouraging visitors to actively adopt a scientific perspective and engage in a process of inquiry

2.2. Using 3D printing to promote cultural heritage

3D printing has proved to be a valuable tool for creating tangible replicas of cultural heritage, making it more accessible to different audiences. In the museum context, it is being used to document and promote objects contained in mummies, such as jewellery obtained by CT scanning of a Human mummy [SSEH23], or bones contained in animal mummies, also obtained by CT scanning [MAC*15]. Realistic 1:1 scale reproductions of human mummies are also being produced to provide tactile experiences that generate strong emotional feedback from visitors [NMS*24]. However, this type of reproduction is extremely complex and reserved for exceptional contexts, such as the mummy of Ramses II in this case. Transparent 3D printing is being explored for education and archaeological documentation, as illustrated by the reproduction of funerary urns. The ‘Secret of Bastet’ project is one such example, offering a 1:1 transparent copy of a cat mummy, based on CT scan data, to reveal its internal contents to visitors.

2.3. Extended reality applications in Egyptology and the study of mummies

The field of Egyptology has also benefited from the integration of XR technologies in museums. Studies are exploring the experience of the general public with virtual, augmented and mixed representations of Egyptological collections [ZRM22]. Interactive exploration of 3D mummy data on 2D touch tables has been experimented with, highlighting the importance of storytelling, such as a guided virtual autopsy to understand the circumstances of death [YRA*16]. VR experiments allow exploration of CT-scan cat mummies, with a virtual curator presenting information and the ability to manipulate objects virtually [RCM*23]. However, the ‘Secret of Bastet’ approach stands out by inviting the user to take on the role of the scientific team that analysed the artefact, virtually carrying out the X-ray and CT scan, observing the bones and deducing the number of specimens. Other initiatives use VR to present stories around heritage artefacts.

Building on this work, the ‘Secret of Bastet’ project breaks new ground by combining a transparent 3D print of the mummy with an immersive virtual reality experience. This approach aims not only to enhance scientific understanding of the mummy, but also to provide an engaging and educational museum experience for the public, going beyond the simple presentation of results to immerse visitors in the discovery process.

3. Context

The cat mummy under study is part of the Egyptology collection displayed in the archaeological gallery of a Fine Arts museum. Within the framework of a research initiative exploring the application of medical imaging and 3D technologies to the investigation of archaeological artefacts, the mummy was subjected to computed tomography (CT) analysis. This examination was conducted

alongside similar scans of two human mummies and five juvenile crocodile mummies housed in the same institution.

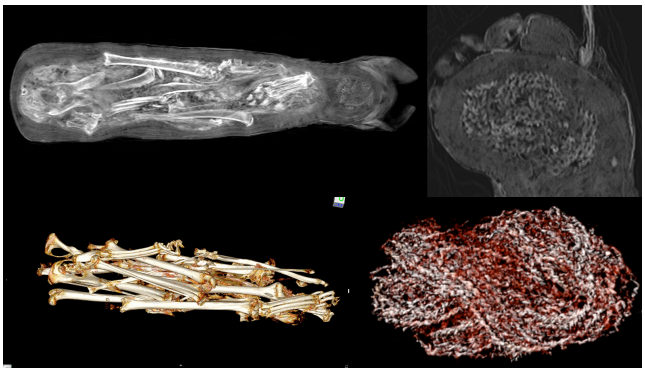

Figure 1: *CT scan of the mummy. Top left: full scan of the mummy. Top right: detail of the head content. Bottom left: Volume rendering of the bones. Bottom, right: Volume rendering of the string ball inside the head*

The CT scan of the cat mummy yielded particularly noteworthy results, revealing an atypical internal structure composed of a tightly packed assemblage of long bones and a distinct spherical mass of braided twine (Fig. 1). These findings contributed to the scientific understanding of the artefact's composition and served as the foundation for the production of 3D data (Fig. 2) that was used to develop augmented reality and virtual reality environments, as well as 3D prints of its internal components (Fig. 3) [GPN*18].

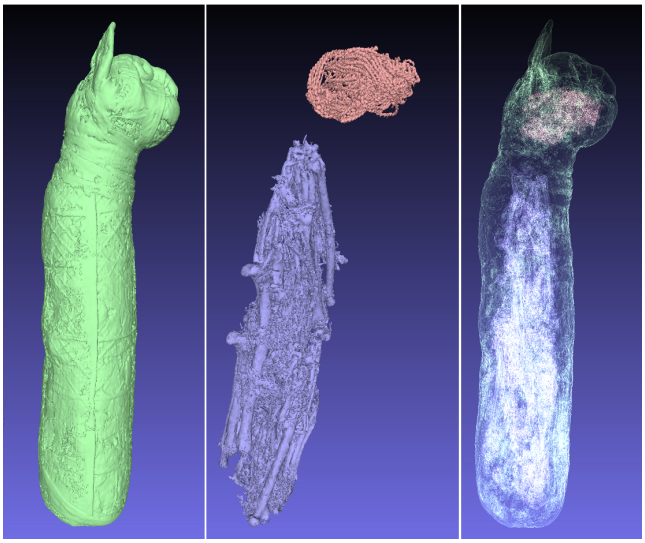

Figure 2: *3D models generated from the CT scan data*

The discoveries resulting from the CT scan analysis, combined with the potential offered by 3D visualisation techniques, prompted a collaborative effort between the scientific team and museum professionals to develop innovative modes of visitor engagement. This collaboration led to the implementation of two complementary interpretive experiences.

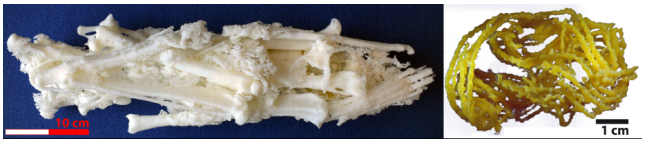

Figure 3: *3D printings of the bones and the string ball*

The first consists of a transparent 3D-printed replica of the cat mummy, designed to provide visitors with a tangible and intuitive means of visualising the internal structures revealed by the CT data. The second experience takes the form of an immersive virtual reality application, aimed at communicating the scientific process underlying the investigation. This includes the methodologies used in medical imaging and the interpretive reasoning that led to key findings, such as the identification of multiple individual felids within the same mummy.

4. Method

The following section outlines the methodologies employed in the design and implementation of the two main components of the project: the transparent 3D-printed replica of the cat mummy and the immersive virtual reality application. Each is presented in turn, detailing the specific processes, technologies, and design considerations involved.

4.1. Design and implementation of the transparent copy of the mummy

This phase was carried out jointly by computer scientists and archaeologists, the curator and the Musée des Beaux Arts outreach team. The design and implementation of the transparent copy of the mummy followed the method described in [NGT*16], which proposed a similar approach for the transparent 3D printing of a funerary cremation urn, for archaeological documentation purposes.

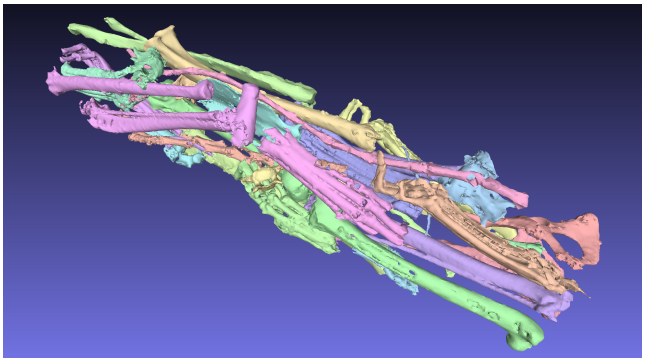

Figure 4: *Segmented 3D models of the bones*

3D models design for 3D printing. The transparent replica of the mummy was developed from CT scan data using a different methodology than that applied to the initial 3D print (Fig. 3). Whereas the first model employed a lower radiodensity threshold—resulting in a single-piece object that included remnants of

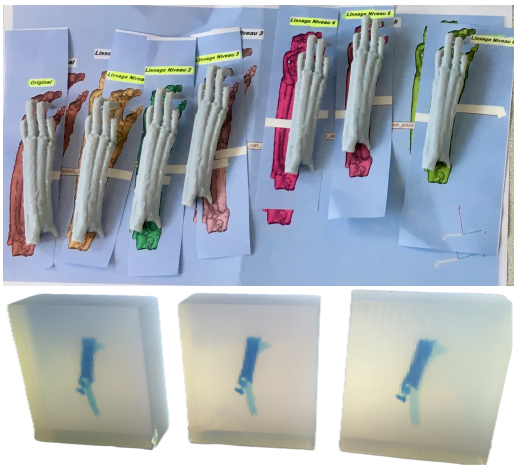

Figure 5: *Design study for bones rendering: Top, smoothness, bottom, transparency*

soft tissue surrounding the bones to facilitate easier handling—this new version adopted a higher radiodensity threshold to isolate only the skeletal remains. This approach aimed to improve the clarity and interpretability of the internal anatomical structures, particularly with respect to distinguishing the individual felid components contained within the mummy.

A total of 31 bone groups were identified, segmented, and reconstructed into separate 3D models while preserving their relative anatomical positions within the mummy (Fig.4). Design optimisation of the printed bones focused on achieving an appropriate balance between surface smoothness and the level of anatomical detail conveyed in the physical rendering (Fig.5, top). The outer shell of the mummy was also digitally smoothed to enhance visibility of the internal structures while retaining volumetric accuracy.

Subsequently, the complete model was digitally filled and then hollowed using Boolean operations based on the internal components, in order to ensure clean separation of resin materials during the 3D printing process. To enhance interpretive clarity, different visual rendering strategies were applied: a high level of transparency was used for bones deemed less relevant, while specific anatomical features—such as nine paws and three partial tails—were rendered in opaque material to draw attention to their form and placement (Fig. 5, bottom).

Production of the transparent 3D copy. The 3D printing of the mummy was produced using a Stratasys PolyJet printer operated by the company CadIndus (https://www.cadindus.fr/).

The printing process duration for the 1:1 copy of the mummy lasted 20h. The respective quantity of material for the 3 resines colors were V-Clear, 3295 g, V-Yellow, 285 g, V-Cyan 139 g, including support matter constituted of 1 095 g of V-Clear and V-Yellow. The total weight of the copy is 2.5 kg.

Once the object was printed, several operations were performed in order to obtain a transparent rendering of the resine: removing of the support matter, photo-bleaching to improve the transparency

Figure 6: *Final result of the transparent 3D printing*

Figure 7: *Various sizes of the transparent 3D printing*

of the resin, sandblasting, sanding, polishing and varnishing for a perfect finish that allows the internal components to be clearly seen (see Fig. 6).

In addition, half-size and 1:8 size copies were produced for promotion and dissemination (see Fig. 7).

4.2. Design and implementation of the VR experience

Design of the experience. The VR experience was conceived to allow users to examine the cat mummy in detail, to manipulate it in ways not possible in a traditional museum context, and to explore the imaging techniques employed by archaeologists in its study. To enhance engagement and support educational outcomes, a gamified sequence was integrated at the conclusion of the experience. Prior to development, a comprehensive graphic narrative design

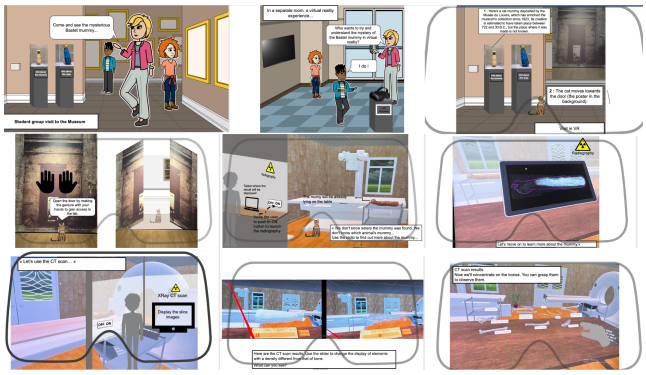

Figure 8: *Visual script for the design of the VR experience*

was created and collaboratively validated by all project partners to ensure coherence between the virtual experience and its physical integration within the museum space. This visual scenario, presented in Figure 8, served as a blueprint for scripting the full experience, including the introductory sequence in the museum's Egyptology gallery, in-application scenes, voiceover and on-screen instructional content, transitions, and the closing sequence. This graphical approach, supported by the UX design team, allowed the interdisciplinary team to collaborate smoothly. This phase took the form of ten 90-minute workshops, held at a rate of two per month over five months. These workshops brought together all the partners: a museum mediator, the archaeologist and the 2 VR scientists who carried out the initial study of the cat mummy, 1 development engineer from the VR laboratory, 1 VR researcher and 2 UX engineers from Orange Innovation, 1 project manager from the Polymorph graphics studio.

To support user orientation and continuity throughout the experience, an animated virtual cat functions as a guide, signaling and facilitating transitions between scenes.

Narrative Structure and Sequence of the VR Application The VR application unfolds across five sequential scenes, designed to mirror a scientific investigation while ensuring narrative continuity and spatial coherence between virtual and real environments. The experience begins in a digitally reconstructed version of the museum's Egyptology gallery, where virtual representations of both the original cat mummy and its transparent 3D-printed replica are displayed (Fig. 9). This introductory setting facilitates a smooth transition from the physical to the virtual space. A voice-over provides historical and archaeological context, including information on the mummy's provenance and discovery.

Users are then guided to an 'observation room', modelled after a museum reserve space. This environment includes a table featuring the mummy, surrounded by other digitised artefacts from the museum's collection. Here, visitors can manipulate the virtual mummy, and a voice-over introduces the next stage of the investigation, prompting further inquiry into its internal composition.

The third scene transports users to a virtual analysis laboratory equipped with two types of medical imaging devices. Visitors first simulate taking an X-ray of the mummy, then proceed to perform a CT scan (Fig. 10). These steps are presented as part of a coherent diagnostic workflow, with the voice-over guiding and contextualising the procedures.

Upon completion of the imaging tasks, users return to the observation room to interact with the scan results. A density slider allows for real-time adjustment of the CT data visualisation, enabling users to differentiate the internal components of the mummy based on material properties. This interactive exploration culminates in a question that prompts users to estimate the number of individuals contained within the mummy by identifying recurring bone structures—thus highlighting an unexpected discovery (Fig. 11).

In the final scene, users are asked to carefully place the mummy back into its container. They are then returned to the virtual Egyptology gallery, concluding the experience with an invitation to re-enter the physical museum space and observe the original artefact.

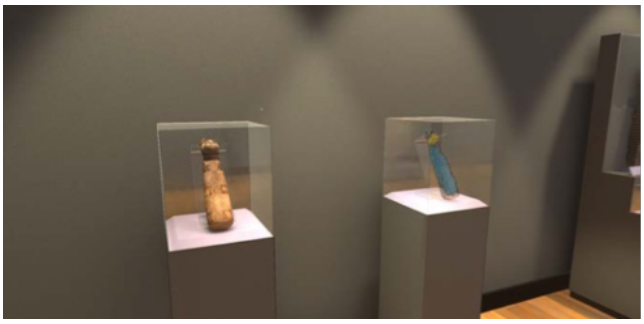

Figure 9: *Replica of the Egyptology room in the first VR scene*

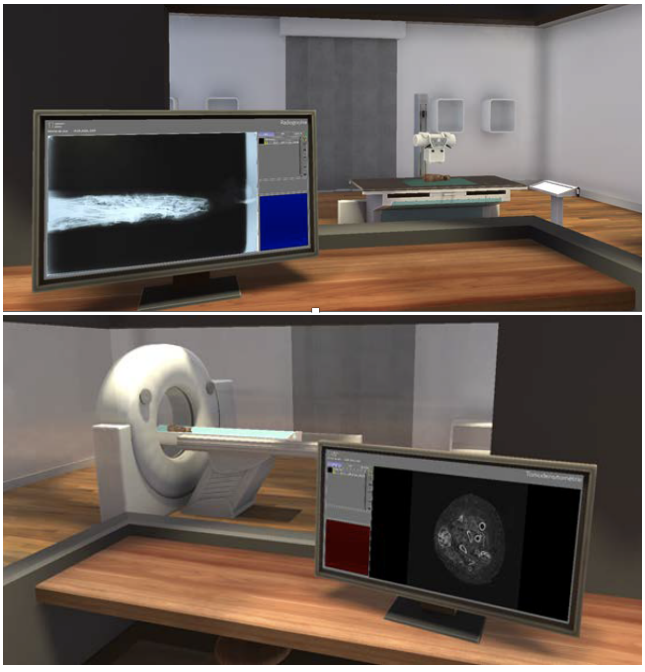

Figure 10: *Radiography and CT scan of the mummy in VR*

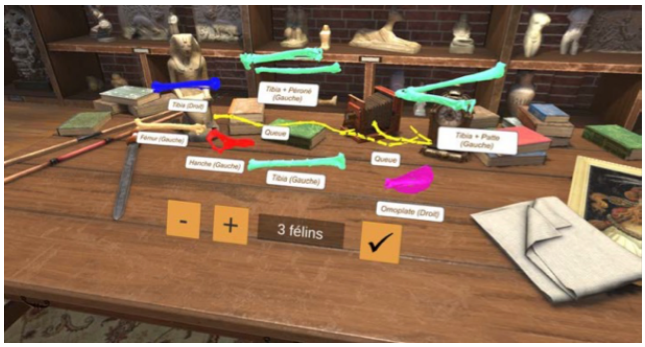

Figure 11: *Analysing the content of the mummy*

Implementation of the VR Application The virtual reality application was developed using Unity 2021.3 and deployed on the HTC Vive Focus 3 head-mounted display (HMD). Interactive behaviours and scenario management were implemented using the Xaerus plugin (https://xareus.insa-rennes.fr/). The application leverages the headset's native hand-tracking functionality to render users' hands within the virtual environment and enable object manipulation. This natural interaction paradigm, grounded in the "virtual hand" metaphor [BKLP01], is particularly well-suited for museum contexts, as it supports intuitive use even among participants unfamiliar with VR technologies. A pinch gesture—defined as contact between the thumb and index finger—is employed to grasp and manipulate virtual objects.

User mobility is intentionally constrained to a 1m² physical area. Scene transitions are automated and accompanied by the animated movement of a virtual cat, serving both as a narrative guide and as a mechanism to avoid complex navigation inputs, thereby ensuring accessibility and maintaining a controlled experience duration. A voiceover provides contextual explanations and guides users through the interactive tasks.

In the observation room, the manipulation of the virtual mummy is subject to constraints: upon release, it automatically returns to its original position. This design choice aims to discourage unrealistic or potentially disrespectful interactions that would be inappropriate in a real-world museum setting.

4.3. Experimental protocol

4.3.1. User study in a XR professional event

The system was presented for the first time at the international trade event dedicated to VR, Laval Virtual. After experiencing the VR application, users were invited to complete a questionnaire on a digital tablet. In addition to gender, age group and level of VR expertise, participants were asked to complete an standard SUS presence questionnaire [SUS94], and a usability questionnaire constitued of six questions. The first four questions aimed to evaluate participants' general impressions of the VR experience through a series of statements rated on a 7-point Likert scale, ranging from 1 ("not at all") to 7 ("very much so"). These statements included: "The device is easy to use," "I am satisfied with this experience," "It was easy to learn how to use," and "I felt emotions during this experience." A subsequent question assessed perceived cognitive impact by asking whether the experience enabled the acquisition of knowledge, with a binary Yes/No response format. Finally, to gauge the influence of the VR experience on visitor motivation, participants were asked whether the device made them want to visit the Musée des Beaux-Arts in Rennes to see the actual cat mummy. Responses to this item were captured using a five-point ordinal scale: "Certainly not," "Rather not," "I don't know," "Rather yes," and "Certainly."

In addition, participants were asked to complete a simplified version of the Simulator Sickness Questionnaire (SSQ) both before and after the VR experience, focusing on a single item designed to assess overall physical comfort. The question—"Are you feeling any general discomfort?"—was answered on a four-point ordinal scale: "Not at all," "A little," "Moderately," or "Severely." In cases where participants reported any level of discomfort beyond "Not at all," they were prompted to specify the nature of the symptoms by selecting from a predefined list, which included: fatigue, headache, eye strain, difficulty focusing, increased salivation, sweating, nausea, difficulty concentrating, head pain, blurred vision, dizziness with eyes open, vertigo, stomach discomfort without nausea, and burping.

4.3.2. User study in the museum

The system was introduced to the public during the national event Museum Night, held at the Musée des Beaux-Arts. Participants were invited to complete a 15-item questionnaire, presented in Table 1, developed by the museum's mediation team to gather qualitative feedback on the experience. Although the questionnaire does not follow a standardized evaluation framework typically used in user studies, it reflects the specific concerns and interests of the museum staff regarding the integration of immersive technologies into cultural mediation practices.

5. Results

5.1. Transparent 3D printing of the mummy

The result of the transparent copy of the mummy produced is both a source of information for discovering the contents of the mummy, and an object of aesthetic interest. The curator of the Fine Arts Museum therefore decided to showcase the pairing of the real mummy and its copy in the museum's Egyptology gallery, using the scenography shown in Figure 12. The two objects are displayed side by side in identical individual display cases, with symmetrical lighting to emphasise them. During the VR professional event, 16 people took part in the evaluation, 10 males and 6 females, with a level of VR expertise evaluated at 3.77/5 (SD=1.1). The age distribution is 2 between 18 and 23 years, 4 between 24 and 29 years, 5 between 30 and 39 years, 4 between 40 and 49 years, and 1 between 55 and 59 years. The presence indicator is 4.4/7, and the usability cores are as follows: 'easy to use', 5.76/7 (SD=1.2), 'easy to learn', 6.46/7 (SD=0.97), 'satisfaction with the experience', 6.38/7 (SD=0.65), 'feeling of emotions during the experience', 4.76 (SD=1.53). Two people reported slight general discomfort after the experience, whereas they had none before (one, eye fatigue=1 and difficulty focusing=1, and the other one, eye fatigue=1). All felt that they had gained knowledge, and 12 said that

Id	Question	possible answers
1	What age group do you belong to?	Under 20, 20-30y, 30-40y, 40-50y, 50-60y, More than 60y
2	Is this your first visit here?	Yes/No
3	What are your expectations of this visit?	Visit the whole museum ; For a guided tour or workshop ; To see one or more possible artworks ; Other
4	Have you ever used a VR device?	Yes/No
5	If not, why?	I did'nt know these devices existed ; I prefer to discover the museum without this kind of device ; I prefer to separate the virtual from the real object ; Other ;
6	Did you enjoy this VR experience?	Yes/No
7	Did this system enable you to get to know this mummy better?	Yes/No
8	For the mummy studied, rate your opinion from 1 to 10 according to these criteria: Knowledge ; Understanding; Thinking; Immersion	Score 1-10 per criteria
9	How did this experience make you feel?	Open answer
10	Have you encountered any difficulties in: using the system ; understanding the content ; carrying out the actions?	Yes/No Yes/No Yes/no
11	Did you feel unbalanced or uncomfortable?	Yes/No
12	What was your favourite experience or discovery?	Open answer
13	What is your overall opinion of this experience?	Open answer
14	Have you ever wanted to go back and see the real mummy?	Yes/No
15	Do you have any other comments?	Open answer

Table 1: *Evaluation questionnaire used by the Museum*

it had made them want to come to the museum to discover the real mummy: 9 "Certainly", 3 "Rather yes", 1 "Rather no", 3 "I don't know".

5.2. User study in the museum

A total of 74 individuals participated in the virtual reality experience, with the evaluation questionnaire administered to the first 40 participants. Among these respondents, 65% had prior experience with virtual reality. The age distribution was predominantly skewed toward younger participants: 32.5% were under 20 years old, 55% were between 20 and 30, 2.5% between 30 and 40, 1.2% between 40 and 50, and 5% between 50 and 60; no participants were over the age of 60. Notably, 52.5% of participants were visiting the museum for the first time. Regarding their primary motivations for attending the event, 77.5% indicated an intention to explore the entire museum, 15% aimed to attend a specific workshop, 1.4% came to view one or more specific artworks, and 2.5% cited other reasons. A visual summary of these demographic and motivational data is presented in Figure 13.

Figure 12: *Integration of the transparent 3D printing next to the real mummy in the Egyptology room of the Museum*

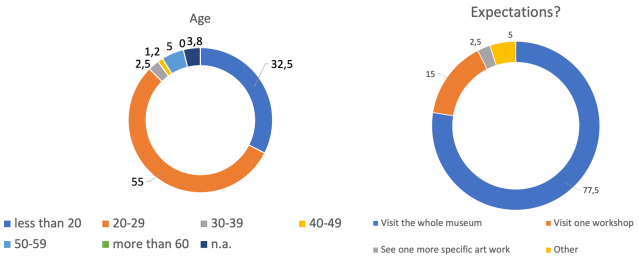

Figure 13: *Participant age ranges and expectations in the Museum event*

The responses to the evaluation questionnaire are summarized in Table 2. Qualitative feedback obtained from the open-ended questions is presented and analyzed in detail in the Discussion section.

6. Discussion

Transparent 3D printing is now part of the museum's permanent exhibition. Although no formal evaluation has been carried out on this aspect, visitors' reactions to the mediators have been very positive, both in terms of the knowledge they provide and the aesthetic aspect. The transparency allows easy and immediate access to the contents of the mummy, while the scenography highlights the original mummy and allows visitors to make the link between

Question	Answers (average)
Did you enjoy this VR experience?	Yes 100% / No 0%
Did this system enable you to get to know this mummy better?	Yes 97.5% / No 2.5%
For the mummy studied, rate your opinion from 1 to 10 according to these criteria: Knowledge Understanding Thinking Immersion	 9/10 8/10 9/10 9.5/10
Have you encountered any difficulties in: using the system ; understanding the content ; carrying out the actions?	 Yes 12.5% / No 87.5% Yes 2.5% / No 97.5% Yes 17.5% / no 82.5%
Did you feel unbalanced or uncomfortable?	Yes 2.5% / No 97.5%
Have you ever wanted to go back and see the real mummy?	Yes 95% / No 5%

Table 2: *Answers to the questionnaire in the Museum*

Figure 14: *Duplication of the transparent copy for another Museum.*

the mummy and the transparent representation without explanation. The digital data still available enabled a second version of the transparent mummy (Fig. 14) to be produced for an exhibition on animal mummies in another museum, without having to remove the one from the Musée des Beaux-arts de Rennes.

The VR application enhances the museum's mediation system by offering an original approach. The VR experience was presented to the public of the Museum from 13 May 2023 during European Museum Night. Since then, regular events have been organised for individuals and groups from 11 years upwards. The opening of the slots is publicised on the museum's website and social networks, as well as by information sent to visitors on arrival at the museum reception desk. The programme is offered free of charge at predefined times to groups of no more than five people in a dedicated area in the visitors' workshop on the museum's ground floor. The sequence lasts 5 minutes per person. To date, over 500 people have used the virtual reality application.

The 2 evaluations that have been carried out involve very different audiences. Visitors to the VR trade event are used to this type of experience, and are therefore more demanding than novice visitors. It is thus satisfactory and encouraging to note the high scores obtained on the usability of the application during the professional event. The level of presence is noted as standard (4.4/7), which is a good result according to this specific population. It's interesting to note that there's a significant age gap between the 2 populations (87.5% aged under 30 years in the museum vs only 37.5% for the professional event). The scores given by visitors to the museum are very high, and show how enthusiastically they are received. One of the museum team's reservations about integrating a VR application into their exhibition was the fear that visitors would lose interest in the original objects. The response to the question 'Have you ever wanted to go back and see the real mummy', which was overwhelmingly positive (95%), allayed this concern. The users really appreciated the system, attracted by the complete immersion offered, the simple handling, the search processes and the information collected. The interface and the quality of the graphical environment have been very well received, as well as the virtual cat.

In the questionnaires collected by the museum, four questions were open-ended to get free fedback from the visitors. Although we did not have access to the full set of open-ended responses, and thus could not conduct a systematic qualitative analysis, the selected comments provided by the museum's mediation team offer valuable illustrative insights that we discuss informally.

The first one dealt with perceived feelings: 'how did this experience make you feel?'. Here is a representative selection of the answers: "*...joy, amusement, curiosity; doubtful but very satisfied and particularly unexpected, very immersive and interesting; the experience makes you want to know more and it arouses curiosity; impressive, immersion in the proposed universe; immersion in the rooms well done; ...a complete experience with a lot of knowledge; desire to cross the room; to cross the room; feeling of reality. ...astonishment and joy, I was happy to learn all this; good integration of the living into the virtual...feeling of discovery; 3-D sensation; very comfortable playful pleasure of discovery and understanding; curiosity and immersion very immersive; a lot of fun instruction and sense of detail; soothing and enriching; fascinating experience it was great!*"

Participant feedback on the experience reveals a predominantly positive reception, characterized by a range of emotional, cognitive, and sensory responses. Users frequently cite feelings of joy, curiosity, astonishment, and a sense of well-being, indicating a high level of emotional engagement. The immersive quality of the experience is consistently emphasized, with particular attention given to the realistic integration of virtual and physical elements, including the spatial design and 3D effects. Many respondents describe a strong motivation to explore the virtual environment further, suggesting a heightened sense of presence and agency. Additionally, the experience is noted for its educational value, effectively balancing informative content with playful interactivity. Overall, the VR environment was perceived as both intellectually stimulating and experientially enriching.

The second one was intended to identify the favorite aspects of the experience: 'What was your favourite experience or discovery?'. The answers were: "*Information about the mummy, handling and studying the bones; what the scanner reveals, handling the bones; the guide cat, handling, analyses with imaging; the virtual reality experience; counting the bones, finding 3 cats; the tactile activities, I would have liked to have had more; exploded view of the bones and above all the animation of the cat, great! The X-ray and the cat; taking the mummy and putting it back in its box; discovering the results of the X-ray and CT scan, the laboratory actions; visualising the inside of the mummy; handling the bones, global vision of the scenes; handling the objects, the question about the number of felines; handling the mummy; discovering a virtual place; X-ray and CT scan part.*"

Participants identified a variety of favorite elements within the virtual reality experience, with a marked preference for interactive and investigative activities. The handling and examination of bones—particularly those of the mummified feline—emerged as a recurrent highlight, suggesting a strong engagement with tactile and exploratory components. The use of imaging technologies, such as X-ray and CT scans, was frequently cited as both informative and compelling, offering insight into hidden aspects of the mummy and contributing to the scientific depth of the experience. Animated features, including the depiction of the guide cat and dynamic visualizations like exploded bone views, were also well-received, adding an engaging narrative and visual dimension. Additionally, participants expressed appreciation for problem-solving tasks, such as counting bones or identifying the number of animals, which reinforced active learning. Overall, the most valued components combined interactivity, scientific discovery, and narrative immersion, enhancing both the educational impact and user satisfaction.

The third open-ended question asked for general feedback on the experience: 'What is your overall opinion of this experence'. The answers were: "*Positive, excellent, satisfying experience, very good experience that deserves to be better known by the public; new, interesting, fun and enriching; seeing a mummy as you never could; I liked it but not completely because of the subject of study; very realistic, immersive and rich experience, it was great, excellent! I liked the imagery; very good and very interesting; it was great; very good idea to keep going; it provides knowledge; the whole thing helps you understand the creators' intention and the archaeologists' approach is understood; helps you understand the object; very interesting immersion in the research process very good, very good experience; it's very precise and interesting; very good change from the usual museum activities.*"

Overall, participants expressed highly positive impressions of the virtual reality experience, frequently describing it as excellent, satisfying, and enriching. The experience was appreciated for its novelty, realism, and immersive quality, with many highlighting its educational value and its ability to convey complex archaeological concepts in an accessible and engaging manner. Several respondents noted that the VR format allowed them to engage with a mummy in ways that would not be possible through traditional museum displays, deepening their understanding of both the object and the research process behind it. The clarity of the creators' intent and the archaeological methodology was particularly appreciated, suggesting that the experience effectively communicated both content and context. Although one participant expressed some reservations related to the subject matter, the general consensus affirmed the experience as a meaningful and innovative departure from conventional museum activities, deserving broader public exposure. Other comments:

A final open-ended question allowed participants to express themselves freely about the experience: 'Do you have any other comments'. The few collected answers were "*It was perfect, very comfortable headset, I'd like to see more interactivity; too short! keep developing these immersive experiences! to discover more things! the computer voice, the speech sounds like little spoken language; very interesting mediation to complement the visit to the collections; little cat excellent guide for the transitions, frustration at not being able to pet it ; I'd still like more.*"

For this final question of the questionnaire, participants reiterated their overall satisfaction with the VR experience, while also offering constructive feedback and expressing a desire for further development. Several users described the experience as "perfect" and appreciated the physical comfort of the headset, indicating attention to ergonomic design. A common theme was the wish for extended content and increased interactivity, reflecting a high level of engagement and a desire for deeper exploration. The inclusion of a guiding character, notably the virtual cat, was highlighted positively for enhancing narrative continuity, though some participants humorously expressed frustration at the inability to interact more fully with it. Suggestions for improvement included refining the quality of the computer-generated voice, which some perceived as lacking natural speech characteristics. Overall, responses suggest that the VR experience was seen not only as a valuable standalone activity but also as an effective complement to traditional museum visits, with strong potential for future expansion and enrichment.

Although our study was not initially framed within the context of emotional experience research, some visitor responses suggest that the digital encounter with an extinct species evoked affective engagement. This observation aligns with recent findings highlighting the role of immersive digital experiences in shaping users' emotional responses in museum contexts [DCW24]. While our data do not support a systematic analysis of these emotional dimensions, these preliminary insights suggest a promising direction for future research on how digital tools contribute to affective heritage experiences.

The fact that the VR experience is free is also an essential factor compared with the prices usually charged (e.g. escape games). The limit in the size of visiting groups allows for good interaction with the mediator in charge of the project.

7. Conclusions

The Secret of Bastet project illustrates the potential of combining 3D reproduction and virtual reality to enhance both the scientific study and public interpretation of cultural heritage. The transparent 3D-printed replica, generated from CT scan data, offers visitors a non-invasive, visually accessible means of exploring the interior of

a mummified cat, while also serving as a durable and transportable exhibit component that supports conservation priorities.

The immersive VR experience complements this by actively involving users in the scientific process—reconstructing steps such as virtual radiography, object manipulation, and osteological analysis. This procedural transparency fosters a deeper understanding of archaeological methods and promotes engagement through interactivity and narrative structure. Notably, user feedback suggests that VR not only enriches comprehension but also heightens the desire to encounter the original object, reinforcing rather than replacing the material experience.

While the project has been widely appreciated for its innovation and accessibility, areas for future development include improving the naturalism of narration, extending content duration, and expanding interactive features. Nevertheless, the integration of immersive digital tools demonstrated here offers a compelling model for museums seeking to bridge scientific research and public engagement, and highlights the value of XR technologies in mediating complex archaeological narratives.

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