From Artefact to Interaction:
A Tangible Smart Replica
of an Ancient Greek Statue

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Abstract

Traditional museums often rely on a "DO NOT TOUCH" policy, which can make cultural heritage feel distant and unengaging. While 3D printing is becoming more common, its potential for interactive learning experiences remains largely untapped. This research explores how a 3D-printed Tangible Smart Replica of an ancient Greek statue, designed as a 3D puzzle, can enhance visitor engagement and information recall while remaining sustainable and practical for long-term integration into museums.

Using a Design-and-Development approach, a functional prototype was built using low-cost 3D-printed materials and open-source electronics. The system consists of a statue puzzle and an interactive base. When a visitor successfully assembles and places the 3D puzzle on the base, the sensors trigger tailored audio-visual narratives. Effectiveness was evaluated through a mixed-methods approach, including A/B testing, the System Usability Scale (SUS), and interviews.

The results indicate a significant increase in both dwell time and information retention compared to traditional static displays. Dwell time increased by 156.3% and retention by 34%. The prototype achieved a Grade A SUS rating, with participants reporting higher levels of emotional investment and curiosity. Qualitatively, the embodied interaction bridged the gap between abstract history and physical reality. While limited by its testing environment, resource and budget constraints, this work provides a blueprint for museums to create interactive exhibits without substantial financial or technical expertise. It demonstrates a sustainable path toward making history more personal, memorable and accessible.

Declaration

I herewith declare that I have produced this paper without the prohibited assistance of third parties and without making use of aids other than those specified; notions taken over directly or indirectly from other sources have been identified as such. This paper has not previously been presented in identical or similar form to any other Irish or foreign examination board.

The thesis work was produced under the supervision of Dr Mark Marshall at the University of Limerick.

ANNIKA JUNGFLEISCH (22359923)
Limerick, 2026

AI Declaration

I herewith declare that I have used artificial intelligence to produce my project and/or report in the following ways:

- Grammarly: Used to review and improve the clarity, conciseness, tone and overall correctness of the written text, including grammar, spelling and punctuation.
- Gemini: Used to modify and enhance a hand-drawn sketch of the Technical Architecture of the System Figure.
- MiniMax Audio: Used to transform text into speech for the digital output of the exhibition.
- Otter.ai and VoxBox: Used to transcribe the interviews.

I further declare that I have discussed this use of artificial intelligence with my supervisor and received permission to use it.

ANNIKA JUNGFLEISCH (22359923)
Limerick, 2026

Ethics Declaration

I herewith declare that my project involves human participants and that I have received approval from the Science and Engineering Ethics Committee prior to undertaking this part of the project. The application number for this project is:

2025_12_08_S&E

ANNIKA JUNGFLEISCH (22359923)
Limerick, 2026

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1 Introduction

Museums have always played a pivotal role in human evolution (Lu *et al.*, 2023). Recently, they have been part of a transformation to keep pace with the fast-moving, evolving society around them (Lu *et al.*, 2023). Museums are evolving from static repositories of cultural heritage into cultural and social hubs for dialogue and informal learning (Pattakos *et al.*, 2023; Chen *et al.,* 2025). This evolution has been driven by an approach that prioritises visitors and demands a deeper emotional and cognitive connection with artefacts (Wilson *et al.*, 2018b; Lu *et al.*, 2023; Chen *et al.*, 2025). Consequently, the traditional "Glass-Case" (Wilson *et al.* 2018a, p.1) paradigm and the "DO NOT TOUCH" (Wilson *et al.* 2018a, p.1) signage, which limits interaction to sight and sound and excludes the powerful senses of touch and physical manipulation, have been challenged.

The transformation described above aligns with another shift that researchers have observed in museums' roles. Their role is transitioning from custodians of objects to facilitators of experience (Marshall *et al.*, 2016; Pattakos *et al.*, 2023). As facilitators of experiences, museums need to prioritise a visitor-centric approach and foster deeper emotional and cognitive connections to cultural heritage. However, this means that visitors have come to expect a more intuitive and multisensory experience (Wilson *et al.*, 2018b; Chen *et al.*, 2025). The core roadblock to interaction has historically been the need to conserve rare objects. (Wilson *et al.*, 2018a). Museums must adopt new strategies to meet these contemporary demands (Pattakos *et al.*, 2023). The successful adoption of this transformation in expectations will further enhance learning in informal environments.

In response, many institutions have experimented with various technological interventions, though results remain varied. For instance, while mobile applications were introduced to provide real-time, place-specific information, they often suffer from "digital escapism," where the interface distracts visitors from the physical collection. This is frequently exacerbated by "app fatigue," poor user interfaces, and technical failures like unreliable indoor GPS. (Hanussek, 2020). Other experiments, such as autonomous guide robots, have moved from focusing on technical navigation toward establishing social rapport through nonverbal cues like eye contact and head gestures (Kuno *et al.*, 2007). In the face of modernisation, even traditional audio guides have seen redesigns.

While modern systems have moved toward location-aware map interfaces, research suggests that visitors often prefer traditional, keypad-based guides due to their familiarity and low cognitive demand (Wacker *et al.*, 2016). These varied efforts highlight a sector-wide commitment to finding visitor-centric mediums that balance technical sophistication with practical usability.

Crucially, this search for effective interaction is supported by the theory of embodied cognition, which posits that learning is significantly enhanced by physical interactivity (Alt *et al.*, 2013; Chen *et al.*, 2025). By grounding abstract information in tangible experience, museums can improve both information recall and visitor engagement (Alt *et al.*, 2013; Chen *et al.*, 2025). This is particularly the case in informal learning environments, such as those found in museums (Chen *et al.*, 2025).

This demand for active, hands-on experiences aligns with the rapid advancement of digital fabrication, particularly 3D printing (Wilson *et al.*, 2018b). 3D printing allows for the creation of high-fidelity, cost-effective replicas of cultural artefacts (Wilson *et al.*, 2018b). While the state of the art for 3D printing is well established in research and conservation, a significant gap remains in its application in public exhibition spaces (Wilson *et al.*, 2018b; Cooper, 2019).

Currently, many museums use 3D-printed replicas as static physical copies, failing to unlock their full potential as interactive learning opportunities (Marshall *et al.*, 2016). Despite their ability to create tactile, high-fidelity replicas, the current practice of using them as static objects underutilises their potential to serve as Tangible Smart Replicas that foster interaction (Lu *et al.*, 2023). This evolution is achievable through the integration of physical computing and proximity-based interaction methods. For example, Near Field Communication (NFC) provides a robust, wireless solution for identifying and tracking objects (Razak *et al.*, 2024). Unlike touch-detection systems, which struggle with environmental factors such as glass reflections and ambient lighting, NFC offers a durable, self-contained method for triggering digital content (Marshall *et al.*, 2016; Pattakos *et al.*, 2023).

By combining these sensors with the modular architecture of platforms like Arduino, curators can adopt a toolkit-based approach, managing exhibits that deliver localised narratives directly in response to physical touch. The central motivation for this project is to sustainably design a replica that bridges the gap between advanced 3D printing capabilities and the long-term, meaningful hands-on engagement required in a modern museum environment. By tran-

sitioning passive, high-fidelity replicas into Tangible Smart Replicas, this research seeks to redefine how visitors explore and connect with cultural heritage.

1.1 Problem Statement and Research Question

Traditional museums rely on barriers and glass to protect their artefacts, limiting visitor engagement and the exploration of an artefact's history, craft and form. This especially affects people who prefer tactile activities for learning. While high-fidelity 3D-printed replicas are being increasingly utilised by museums to overcome the historical “don't touch” barrier mentioned previously, the absence of a fully integrated, sustainable, and effective design methodology for Tangible Smart Replicas within a permanent museum setting remains.

While existing research and prototype projects show the potential of Tangible Smart Replicas, museums require solutions that are durable, cost-effective to maintain and easily integrated and adaptable by the museum staff without constant external technical support. This critical gap between technological feasibility and operational sustainability in a museum context defines the central problem addressed by this project. Consequently, this research is guided by the following core question:

> *How can a 3D-printed Tangible Smart Replica of an Ancient Greek Statue be designed to improve visitor engagement while remaining sustainable and practical for long-term museum integration?*

Answering this question involves investigating the optimisation of the replica's design and fabrication. It involves balancing the physical authenticity of the object with embedded digital technology, ensuring material durability, and utilising technology to create a seamless, intuitive, "walk-up-and-use" interaction. Furthermore, the design must prioritise the long-term sustainability and practical requirements of the museum institution.

To address these challenges, this research focuses on a specific form of tangible interaction: a puzzle-based replica of an ancient Greek statue. The subject chosen for this project is one of the Caryatids of the Erechtheion. As one of the most iconic ensembles in classical architecture, the Caryatids offer a high degree of familiarity for visitors, making them an ideal candidate for testing how tactile, fragmented interaction can deepen the public’s connection to world-renowned cultural heritage.

1.2 Aims and Objectives

To address the central research question, this work focuses on the following aims:

- Design and Fabrication: To design, develop and evaluate a 3D-printed prototype of a scaled-down, Tangible Smart Replica of one of the Caryatids of the Erechtheion that is sustainable and practical for long-term museum integration and segmented into a magnetic puzzle.

- Interactive System Integration: To integrate reliable technology and digital outputs to provide a rewarding and educational experience upon correct assembly of the replica.

- Evaluation and Practicality: To investigate the impact of tangible puzzle-based interaction on museum visitor engagement and information recall.

- Safety: To create a final replica that is safe for handling.

Out of the above aims, the following objectives were derived:

- Design and Fabrication: The replica shall be durable (assembled 100 times without damage), and the design shall prioritise robust and cost-effective materials for ease of maintenance.

- Interactive System Integration: The NFC trigger shall ensure that the audio and visual outputs provide an immediate (within 2 seconds) and logical reward upon puzzle completion.

- Evaluation and Practicality: A/B testing, surveys, the System Usability Scale, and interviews shall compare the replicas' impact on visitor engagement, measured by recall and enjoyment, with that of a traditional museum experience.

- Safety: The replica shall be safe for unsupervised public handling, with all components using non-toxic materials and with the embedded electronic system never exceeding 5 volts (5V).

1.3 Report Structure

This report is structured into seven chapters, presenting the research from its background context through to its conclusion.

Chapter 2 provides a comprehensive literature review. It explores the theoretical and contextual background of this project, covering embodied cognition and experiential learning, digital fabrication in museums, interactivity in museums, and the longevity and sustainability of 3D-printed replicas. This chapter also covers the technical foundations for Tangible Smart Replicas. Existing related work is analysed to contextualise this project and to identify and address gaps in this area.

Chapter 3 presents the methodology employed. This chapter outlines the Design-and-Development approach taken to bridge the theoretical understanding of museum interactivity with the development of a functional prototype. Additionally, it lists the acceptance and evaluation criteria, project constraints and the ethical considerations for this project.

Chapter 4 outlines the practical execution of the project, tracing the development from initial concept to physical realisation. It encompasses the contextualisation phase, the prototyping and fabrication stage, and finally, the user testing procedures.

Chapter 5 presents the results obtained from the user testing and the expert interview. This includes quantitative data from the Knowledge Quiz, the System Usability Scale, and Likert scales, as well as qualitative results from interviews and observations.

Chapter 6 discusses the findings presented in the previous chapter. This involves interpreting the results, explaining their significance, answering the research question, and comparing them with existing research. It also considers the implications of the research and reflects on the project's limitations.

Finally, Chapter 7 concludes this research report. It summarises the project's main contributions, limitations, and key directions for future research and development.

2 Literature Review

2.1 The Theoretical and Contextual Landscape

2.1.1 The Evolution of Museum Interaction

As previously mentioned, there has been a significant shift in the role museums play in society. Scholars have challenged the traditional view of museums as collection-based institutions serving only the higher social sector (Lu *et al.*, 2023). They further established that museums need to incorporate technology to meet the demand for a more visitor-centric approach. They found that Technology and Museum Visitor Experiences (TMVEs) have experienced exponential growth since 2017, based on a critical assessment of 122 studies on TMVEs and a systematic tracking of the progress of existing studies in this field. The term TMVEs encompasses a wide range of technological applications, evolving from basic computer displays and multimedia kiosks to smart technologies such as augmented reality (AR) and virtual reality (VR).

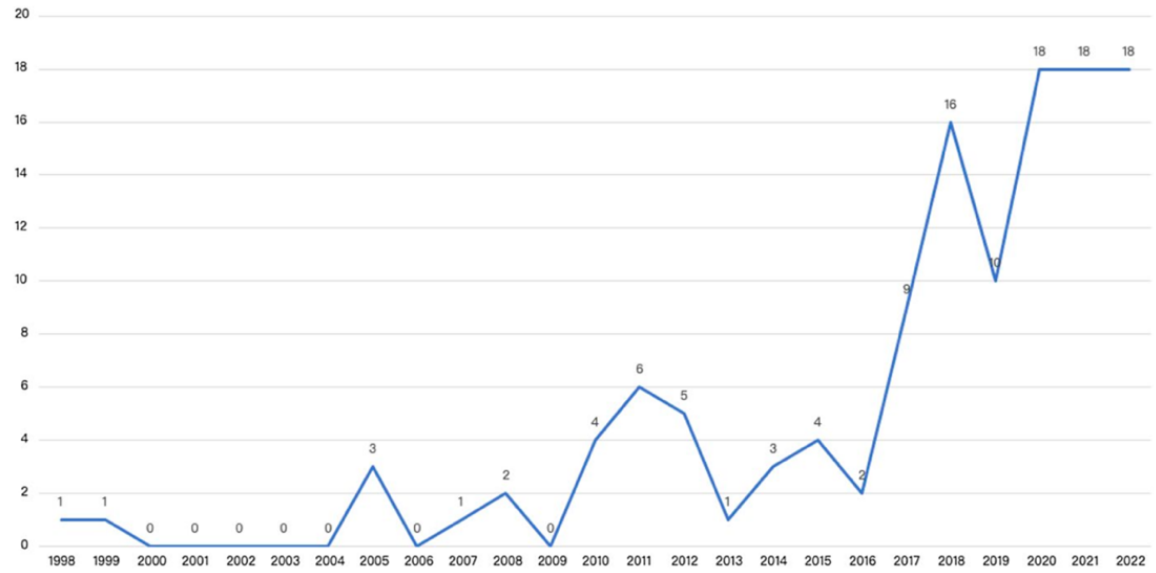


Figure 1: Growth in Research on TMVEs in Lu et al. (2023, p.157)

Lu et al. (2023) further found that research has shifted over time, from an early focus on learning and interaction to contemporary explorations of satisfaction, enjoyment, and virtual presence. The technologies used in museums have also evolved. Especially in the "Futuristic Innovation" stage (2017–present), under which the proposed research falls, studies increasingly emphasise the use of 3D printing and physical computing to create immersive, personalised, and multisensory experiences. These findings support the experiential approach of this proposed research project. By incorporating NFC technology and physical computing into a tan-

gible, 3D-printed replica to foster a deeper connection between the museum and its visitors, the replica aligns directly with the findings of Lu et al.'s (2023) study. As research on TMVEs continues to grow exponentially, this project is becoming increasingly relevant.

However, this method of analysis has several limitations. The paper itself notes that the literature is fragmented, with limited contributions to high-impact journals. This highlights the need for future, theoretically informed, and methodologically sound research.

Successfully implementing these complex digital-physical experiences requires a fundamental shift in how museum exhibits are produced. Petrelli et al. (2016) argue for a co-creation approach that bridges the gap between different professional perspectives.

> *"While curators think "Will visitors like it?", designers think "Will visitors get it?" and technologists think "Will visitors break it?"" (Petrelli et al., 2016, p.3).*

This collaborative mindset was central to the development of this project, specifically during meetings with the Curator for Education at the Hunt Museum. By moving away from the traditional model where technology is a black box provided by external contractors, this project adopts the "Do-It-With-Others" philosophy. This ensures that the resulting tangible interactive is not merely a technical add-on, but is grounded in both pedagogical goals and technical feasibility through a practice-based creative process (Petrelli *et al.*, 2016).

This shift towards multisensory engagement is further supported by Schou and Løvlie (2020), who highlight the turn from passive to active experiences. They argue that museum interaction is moving from a "pedagogy of walking" (Schou and Løvlie, 2020, p. 2), where visitors passively observe, to a "pedagogy of feeling" (Schou and Løvlie, 2020, p. 2), where technology is used to facilitate an emotional connection with the past. Their project, "The Diary of Niels", utilised tangible interaction with physical objects and Radio Frequency Identification (RFID) sensors, a wireless technology that uses radio waves to automatically identify, track, or monitor inanimate and living objects, to create a seamless narrative experience. This aligns with the "Futuristic Innovation" phase introduced by Lu et al. (2023) by demonstrating how physical computing can bridge the gap between historical data and visitor empathy (Schou and Løvlie, 2020).

Another study demonstrating the practical feasibility of technology in museums was conducted by Bonora et al. (2021), who argue that combining Structure-from-Motion (SfM) pho-

togrammetry, a technique that constructs 3D models from 2D image sequences, and 3D printing offers a sustainable, non-invasive alternative to traditional plaster casting. Their workflow validates how reality-based 3D models can be transformed into physical replicas for preservation and display, bridging the gap between digital digitisation and physical presence in the museum environment. In the context of the proposed study, the term replica refers to an exact copy of an artefact at a smaller scale. The proposed study uses a similar approach to Bonora et al. (2021), in which the model was 3D-scanned with an Artec Eva scanner that captures form and colour.

To further strengthen the case for technology in museums, this literature review explores three case studies. The first case study is Pattakos et al. (2023), who installed an interactive display case in the National Historical Museum of Greece. They argued that museums can move beyond the no-touch policy by creating interactive display cases that combine physical engagement with digital responses. This modern case study details the design and implementation of an interactive museum display that combines touch-based engagement with artefacts and storytelling content (figures 2 and 3). However, they encountered numerous touch-detection issues due to reflections from the glass and overhead lighting, leading them to conclude that interactive display cases may require further revision before implementation.

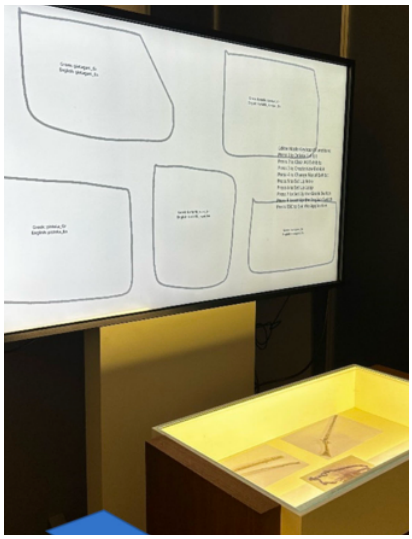


Figure 3: Layout of the interactive display case in Pattakos et al. (2023, p. 6)

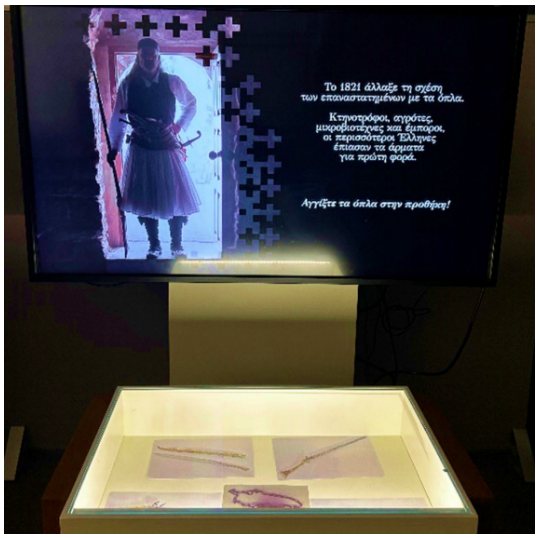


Figure 2: In-lab prototype of display case in Pattakos et al. (2023, p.7)

These findings are crucial because they suggest that relying solely on touch detection is unsustainable. Including non-visual, proximity-based interactions, such as NFC, which are intro-

duced in Marshall et al. (2016), is a more robust solution for durability and self-contained operations across various exhibition environments.

Nevertheless, the display case offered a solution that did not impact the artefact. The project's success was demonstrated by its shift from a laboratory prototype to a permanent installation at the National Historical Museum of Greece. This demonstrated the feasibility of the technology in museums and that interactive displays can operate at scale and be accepted in museum settings, supporting its real-world impact.

A similar approach was explored by Marshall et al. (2015) at the Museon in the Netherlands, where four interactive cases were used to create a competition between objects from the museum's deposit. While Pattakos et al. (2023) focused on touch-based engagement with a permanent collection, the Museon project used personification and humour to give objects a personality. This helped curators to see which object would generate the most interest and should remain on the exhibition floor. Both projects demonstrate the feasibility of interactive cases in museum settings, but they differ in their engagement strategy. Pattakos et al. (2023) utilised storytelling through touch, whereas Marshall et al. (2015) utilised social media and physical presence to foster an emotional connection with the objects.

When directly comparing the two interactive case projects, two very different challenges became clear. Pattakos et al.'s (2023) study highlights the technical challenges of glass reflections and touch detection, while Marshall et al.'s (2015) project highlights the social challenges of visitor participation, noting that visitors were often reluctant to interrupt their visit to use social media. While Pattakos et al. (2023) successfully moved from a laboratory prototype to a permanent installation, the Marshall et al. (2015) project serves as a reminder that interest is a multifaceted metric that is heavily influenced by the physical flow of the museum environment. The proposed project should account for both factors when choosing a technology and positioning the exhibit in the museum.

A third project using technology in a museum is by Marshall et al. (2016). Here, 3D printing and NFC were among the technologies used. Using this technology and other crafts, replicas of artefacts were created for museum visitors to carry around the exhibit, unlocking an additional layer of content by placing the replicas next to interactive cases. The objective was to present the design, creation, implementation, and deployment of Tangible Smart Replicas (TSRs) in a large-scale museum exhibition. By doing so, they demonstrate that TSRs can suc-

cessfully be deployed long-term in a museum exhibition. Marshall et al. (2016) further provided details on the exhibition's design. The exhibition should be designed so that digital content is treated as a core component rather than an optional addition.

Crucially, while this study validates the use of the replica as a control mechanism, it does not investigate the impact of a puzzle-based physical interaction, such as assembling a 3D object, that the suggested research is introducing, on engagement and recall. The proposed research builds on Marshall et al. (2016) as a foundation while further exploring game-based learning and design.

The results of these studies indicate that technology in museums is no longer optional but a necessity for fully engaging visitors in the exhibition. Although the necessity (Lu *et al.*, 2023) and feasibility (Marshall *et al.*, 2016; Pattakos *et al.*, 2023) have been established, the optimal design for improving learning outcomes through embodied cognition and a tangible assembly puzzle remains under-researched and is the focus of this proposed project.

However, it is important to acknowledge the technology that was implemented in museums that fall outside the TSR category. As this research falls into the post-smartphone era, it is important to reflect on the use of smartphones in museums. Over the past decade, museums have been developing mobile applications as a primary means of enhancing visitor experiences through real-time, place-specific information (Hanussek, 2020). However, after over a decade of development, the effectiveness of these apps remains contested. He argues that many museum apps still suffer from “digital escapism”, in which the technology inadvertently distracts visitors from the physical collection rather than augmenting it. Especially, considering the following statement:

> *“Trying to emotionally connect with an exhibit and its story read by a Google translator-esque voice was impossible for me." (Hanussek, 2020, p.210-211)*

This tension highlights a critical challenge in museum innovation: the need to balance digital information with the physical presence of the artefact (Hanussek, 2020).

To counter the distractions of mobile devices, this research follows the design philosophy established in the 'meSch' project, “Do it together”, where "screens were intentionally disregarded so as to encourage visitors to stay present to their bodily experience, and to leave their sight free to explore their surroundings" (Petrelli *et al.*, 2016, p. 4). This bodily experience is

heightened by physical manipulation, as Petrelli et al. (2016) observed that "holding an object to select content empowers and engages visitors more than pressing a button would do" (Petrelli *et al.*, 2016, p. 11). This confirms that hand-held objects provide a more immersive and empowering interface than traditional screen-based or button-operated museum guides. This further supports the proposed usage of a hand-held statue replica.

In addition to mobile applications, museums have experimented with autonomous and semi-autonomous robots to facilitate visitor interaction. Kuno et al. (2007) argue that while early museum robots focused primarily on technical autonomy, the recent shift in museum philosophy mentioned at the beginning of this literature review requires a focus on friendly interaction through nonverbal behaviours. While Hanussek (2020) warns against the “digital escapism” caused by poorly designed museum apps, Kuno et al. (2007) showcase the evolution of guide robots who mimic human social cues, such as head gestures and eye contact, to establish a sense of mutual engagement that grounds the visitor in the exhibition space (Kuno *et al.*, 2007). Furthermore, they propose a more intuitive interaction model than is reviewed by Hanussek (2020) by employing natural nonverbal behaviours like mutual gaze. Robots can bypass the usability issues of mobile interfaces to create immediate rapport with the museum audience.

While previous efforts have focused on high-tech interventions such as robots (Kuno *et al.*, 2007) and mobile applications (Hanussek, 2020), museums are also continually redesigning more traditional tools, such as the audio guide, to improve the visitor journey. Wacker et al. (2016) highlight this ongoing evolution by comparing traditional keypad-based audio guides with modern, location-aware map interfaces. Their study suggests that as museums move away from linear information delivery toward more spatial, information-based systems, they are constantly testing the balance between technical sophistication and user acceptance. These diverse experiments demonstrate the sector's ongoing commitment to finding the most effective medium for visitor-centric experiences.

2.1.2 Design Criteria for 3D-printed Replicas in Museums

Replicas have been shown to provide tactile access to fragile artefacts (Cooper, 2019). However, the current limitation is not the lack of replicas but their application. She states that some museums restrict the handling of 3D-printed replicas due to the cost or conservation concerns about the replicas themselves. This highlights that, for a replica to be sustainable

long term in a museum and to increase visitor engagement, it must be easy and inexpensive to repair or replace in the event of damage. Museum staff will also need to be taught how to maintain and repair the replica. Without proper explanation, the 3D-printed replica risks being ineffective. Visitor interaction and interpretation must be prioritised, not just the protection of originals, as hands-on handling that originals cannot withstand will prove vital to an improved learning experience (Cooper, 2019).

The subsequent study provides further proof of the usefulness of digitally fabricated replicas in museums. Wilson et al. (2018b) investigated how museum visitors perceived the physical properties of 3D-printed replicas and which properties they preferred, focusing on realism, durability and multisensory engagement. The study concluded that poor quality prints reduce engagement and visitor satisfaction. Children valued robustness and durability more, while adults preferred realism, suggesting that future replicas should be robust and durable as well as realistic to appeal to all visitors (Wilson *et al.*, 2018b).

In an interview with the Curator for Education and Outreach at the Hunt Museum in Limerick, Maria Cagney (January 2026), provided more information about the choice of material for museum replicas. The interviewee stated that the choice of material for 3D-printed replicas involves a trade-off between cost, safety, and authenticity. Weight is a critical factor for a memorable and authentic experience. If replicas feel too light, such as a PLA print with a low infill, they can break the immersion. Resin was noted as a more durable, smoother material, but it requires a higher upfront investment and is therefore not always feasible.

"Budget does come into it, you know?" (Cagney, 2026)

The efficacy of 3D-printed replicas is further demonstrated by the increased dwell time observed in tangible installations. Schou and Løvlie (2020) found that when visitors were encouraged to manipulate physical objects to trigger audio narratives, they spent significantly more time in the exhibition space compared to traditional displays. Furthermore, they observed that tangible interactives naturally facilitate social interaction. Families often shared the experience with different members. This collaborative engagement reinforces the idea that tactile replicas serve as social magnets, encouraging collective meaning-making through shared physical touch (Schou and Løvlie, 2020).

This commitment to a presence-based experience extends to the interaction's auditory design. Petrelli et al. (2016) found that the method of audio delivery significantly impacts how a visitor perceives the historical narrative. In their study, participants explicitly favoured sound-in-place over personal devices. They noted that “sound in the headphone isolates, it becomes your own thoughts. Sound in place—like here—it is a narrative that comes directly from this place, that past” (Petrelli *et al.*, 2016, p. 5). By utilising ambient audio triggered by the replica rather than individual headsets, this project, as well as the proposed research, ensures that the narrative remains a shared, social experience. Furthermore, as previously mentioned, physical manipulation enhances this delivery. Petrelli et al. (2016) established that holding an object engages visitors more than simply pressing a button. This design choice ensures the technology acts as a bridge to the physical environment rather than a barrier.

Beyond the creation of replicas, the sustainability of interactive exhibits depends on the ease of management for museum staff. Marshall et al. (2015) addressed this by using NFC cards to allow curators to quickly swap digital content for different objects. This toolkit approach mirrors the requirement for inexpensive and easy-to-repair systems established by Marshall et al. (2016) and McDermott et al. (2014) elsewhere in this review. By enabling curators to update displays with a simple tap of a card, the Museon project reduces the technical barriers that often lead to the failure of complex museum technology.

Marshall et al. (2016) further underline this choice by stating that the "cost and ease of creation (also for replacements) were paramount for the museum when deciding on how to create [replicas]" (Marshall *et al.* 2016, p. 4).

In an interview with the Curator for Education and Outreach at the Hunt Museum in Limerick (January 2026), the interviewee stated that the primary barriers to implementing interactive exhibits are not the technology itself, but the logistical and financial framework surrounding them. There is a significant gap between the expertise of game designers and museum educators. Staff often feel "scared" of the technology, and internal knowledge is frequently lost when specific employees leave. Additionally, funding is usually project-based rather than systemic.

A critical justification for the use of a Tangible Smart Replica over other digital applications is provided by a comparative study of interaction modes. Petrelli and O’Brien (2018) found that mobile phones were the least preferred mode of interaction, compared with replicas and

smart cards. Visitors stated that they preferred replicas over phone applications and smart cards because they are playful, physically engaging, and simple to use.

Schou and Løvlie (2020) address this preference directly, stating that smartphones are often seen as a distraction that pulls the visitor away from the very artefacts they are meant to explain. By using a hybrid approach where the technology is embedded within physical objects, they found that visitors remained more present in the museum environment. However, they also identified a challenge in place-sensitivity, the location in which the exhibit is placed and its relation to the visitor path. While visitors engaged deeply with the tangible narrative, they often failed to connect the digital story to the specific physical room around them. This suggests that for a 3D-printed replica to be successful, it must not only be tactile but also explicitly grounded in its spatial context to ensure a holistic visitor experience (Schou and Løvlie, 2020). They reference Ciolfi and McLoughlin (2011), who created three considerations when designing tangible interactions in a museum landscape:

> *"1. Both digital and physical components must fit well within an overall storyline.*
> *2. Tangible artifacts need to be place-sensitive, in order to avoid distracting from the museum setting.*
> *3. The tangible artifacts should be limited to a simple and straightforward functionality, in order to work as "bridging" components between the digital and physical, rather than "high-tech gimmicks"."*
>
> *(Schou and Løvlie (2020) referencing Ciolfi and McLoughlin (2011), p. 3)*

The preference for tangible replicas over mobile apps is often rooted in the significant technical and practical barriers associated with the latter. Hanussek (2022) identifies app fatigue and severe utility issues as major deterrents. He notes that industry-standard apps from world-leading institutions often lack a user-friendly interface and have limited functionality. While mobile apps are intended to act as invisible companions for visitors, they frequently fail due to poor indoor GPS navigation and inconsistent object cataloguing (Hanussek, 2020). These findings further justify the shift toward Tangible Smart Replicas, which provide immediate, walk-up-and-use interaction without the barrier of a high-bandwidth download or complex digital navigation.

This is further supported by user acceptance studies of more traditional museum guides. For instance, Wacker et al. (2016) found that, despite the theoretical advantages of digital maps and automatic self-localisation, visitors awarded the highest usability scores to the traditional physical keypad due to its familiarity and low cognitive demand. This finding is particularly relevant to the design of Tangible Smart Replicas. It suggests that for an interaction to be successful, it must offer a low-barrier entry point. Just as the physical keypad outperformed complex digital maps in usability, a physical replica provides an intuitive interface that allows the visitor to engage with the exhibit without the frustration often associated with app fatigue (Wacker *et al.*, 2016; Hanussek, 2020).

Achieving the necessary fidelity for these replicas remains a technical challenge. Bonora et al. (2021) identify several critical issues in the digitisation-to-production pipeline, particularly regarding the precision of the hardware used. They note that choosing the right 3D printer is complicated by a lack of industry transparency, stating:

> *"No standardized procedures are established to define the accuracy of a 3D printer, and this is generally an indication that is missing from the datasheets." (Bonora et al., 2021, p. 13)*

This highlights the importance of the post-processing stage, such as glueing pieces of the statue together with special resin and plastering their junctions, to bridge the aesthetic gap between the raw FDM plastic and the material expectations of the visitor.

The transition from passive observation to active participation is further exemplified by the use of 3D puzzles in cultural heritage education. Liao and Noor (2023) demonstrated that 3D-augmented puzzles promote sensory immersion and authenticity by allowing users to physically reconstruct historical artefacts. Their study of the Zenghouyi Bells revealed that tangible assembly, coupled with immediate auditory and visual feedback, significantly enhances heritage learning and engagement compared with traditional methods. This supports the embodied interaction approach of the proposed project, suggesting that the physical reconstruction of the Caryatid replica serves as a cognitive hook that incentivises the visitor to explore deeper historical narratives (Liao *et al.*, 2025).

2.1.3 Interactivity and Engagement

As established by Lu et al. (2023), museums are moving from passive collection-based institutions to a more visitor-centric approach. Dynamic experiences achieved through enhanced interactivity are among the most effective means of achieving this desired engagement (Pallud, 2017). This proposed research adopts her definition of interactivity as "the extent to which users can participate in modifying the form and content of a mediated environment in real time" (Pallud 2017, p. 469).

Pallud (2017) provided further empirical evidence that when users perceive museum technology as interactive and intuitive, they experience higher levels of cognitive engagement. Cognitive engagement is a concept comprising attention, enjoyment, and curiosity. This is a crucial finding as she determined that cognitive engagement is a significant predictor of learning and recall in a technology-mediated museum setting. Thereby connecting successful interaction design directly to educational outcomes. The link between physical interaction and learning is further supported by Pallud (2017), who demonstrates a positive and significant relationship between Interactivity and Cognitive Engagement. Her research shows that "the more users perceive the medium as being rich and interactive, the more likely they are to be engaged and involved in their experience" (Pallud, 2017, p. 469).

This aligns with previous studies, such as those by Shaw (Pallud, 2017 referencing Shaw, 1985), who demonstrated that enjoyment is one of the most important factors for learning in an informal learning context such as museums. Therefore, museum exhibitions should aim at generating interest and curiosity, as many visitors today are curiosity-driven public who seek to maximise the value of their visit (Pallud, 2017). This indicates that the two core components of visitor engagement in museums are education and entertainment. Her research further suggests that the solution to how museum technologies enhance learning lies in providing an interactive and easy-to-use experience. Evidently, the design of the interactive system proposed in this research must be clear and robust to achieve a high level of perceived interactivity and ease of use.

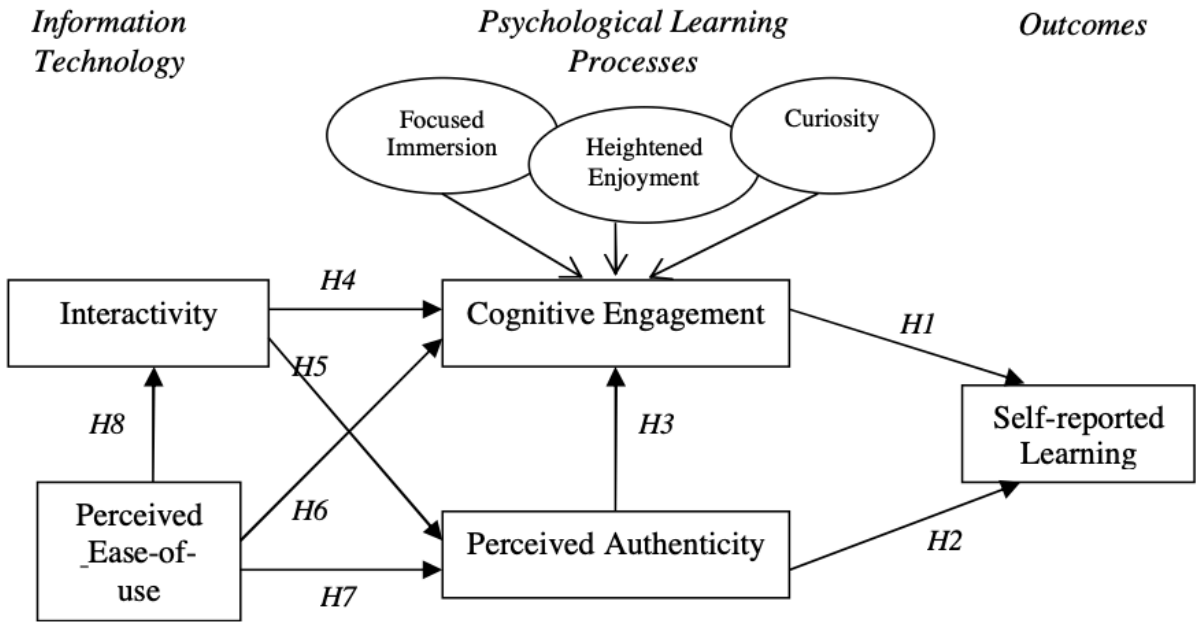


Figure 4: Pallud's Research Model in Pallud (2017, p. 468)

To summarise, the feasibility of incorporating digital feedback into tangible objects was demonstrated by Marshall et al. (2016) as previously mentioned. Establishing the concept of using replicas as a control mechanism offers a simple, walk-up-and-use interaction to trigger tailored content. This approach directly addresses the necessity for ease of use established by Pallud (2017).

Furthermore, the link between interaction and recall is well-supported by Alt et al. (2013). They found, in their work on public display applications, that interactivity significantly increases recall of displayed information. This reinforces the validity of the proposed project's prototype.

Wilson et al. (2018b) provide further evidence of replicas improving engagement. In their study, 93% of interviewees reported that a 3D-printed, tactile replica would enhance their museum experience, and 36% further reported that it would increase their understanding and enjoyment of the exhibit.

Interactivity and ease of use lead to higher cognitive engagement (Marshall *et al.*, 2016; Pallud, 2017), which in turn is a strong predictor of improved recall (Alt *et al.*, 2013; Pallud, 2017). This research project directly addresses this framework by designing a tangible, puzzle-based replica to maximise embodied participation and curiosity. Thereby aiming to optimise cognitive engagement and improve visitor learning outcomes.

2.1.4 Embodied Cognition and Experiential Learning via Gamification

Embodied Cognition is the concept that cognitive processes are deeply rooted in the body's interactions with the world. Thinking is not purely an abstract process occurring in the brain but involves the body, sensory input and interaction with the immediate environment (Chen *et al.*, 2025).

Chen et al. (2025) identify four dimensions necessary for a successful embodied experience.

1. Experience Foundation & Experience Mapping (Mapping Dimension): The visitor needs to understand the structure of the interaction.
2. Sensory, Functional & Interactive Experience (Perception Dimension): The point of physical interaction.
3. Scene & Social Experience (Situational Dimension): The creation of the contextualisation.
4. Emotional Identification (Meaning Construction Dimension): The outcome leads to a profound understanding of cultural heritage.

For museum experiences, this theory suggests that reception should shift from a purely rational cognitive level to a deeper, embodied experience. Learning is enhanced when the visitor's body is activated in the experience. When a visitor physically manipulates a tangible object, such as the puzzle-based replica used in the proposed research, they are engaging in sensory, functional, and interactive experiences. This enhanced experience shifts the visitor's role from a passive recipient of information to an active experimenter and will not only improve engagement but also increase information recall (Chen *et al.*, 2025).

Both Chen et al. (2025) and Pallud (2017) share similar outcomes. As learning in a museum is "non linear, self-paced, voluntary, and exploratory" (Pallud 2017, p.468), and visitors are driven by curiosity about the exhibition topic, the method of engagement is to the educational outcome.

To address this, this project leverages the concept of Tangible Embodied Interaction (TEI), a theoretical model in which physical objects, such as the puzzle-based replica, are used to connect visitors with intangible values, such as the replica's history and mythology (Theodoropoulou *et al.*, 2022). This physical approach is combined with the dynamics of Game-Based Learning (GBL). They found that exploiting the dynamics of games in Cultural Heritage is an essential

means of fostering familiarity with an artefact, maximising motivation, enhancing engagement, and activating curiosity, thereby leading to a deeper understanding of the content.

In an interview with the Curator for Education and Outreach at the Hunt Museum in Limerick (January 2026), Cagney noted that providing rewards works exceptionally well for incentivising learning and that encouraging "playfulness" through puzzles or tabletop-style interactions helps visitors remember the experience longer than a standard walkthrough.

Theodoropoulou et al. (2022) explored another area related to this proposed research, object-driven narrative paths. Using scenario customisation, which allows visitors to choose different routes, aligns with the idea of letting visitors decide which place to position the replica first, thereby revealing various snippets of information in a unique sequence. This research adopts a similar approach, offering visitors six options for placing the replica, each unlocking different information snippets.

However, some replicas can compromise engagement, as some visitors struggle to grasp the intended use of the replicas or fail to make the crucial connection to the original artefacts (Marshall *et al.*, 2016). The puzzle mechanism directly addresses this critique by providing an inherent, self-evident goal, assembly, before the digital reward is triggered. Additionally, information screens and signs support the proposed prototype and thereby forcing clear intent. Furthermore, assembling the puzzle often requires reference to the original statue for guidance, which can increase visitors' awareness of and attention to the original artefact. This mitigates the risk that visitors overlook the originals when using the replicas.

This proposed research applies the TEI model to foster embodied cognition, employs GBL to maximise motivation and curiosity, and addresses known usability issues, aiming to significantly increase cognitive engagement and, subsequently, visitor learning and recall.

2.1.5 Modalities of Feedback: Tactile, Auditory, and Visual

The shift from the traditional "under glass" (D'Agnano *et al.* 2025 p. 207) museum paradigm towards interactive engagement is driven by the consensus that activating multiple sensory channels enhances memory retention and deepens information processing (Chen *et al.*, 2025). This approach is rooted in the concept of embodied cognition. They developed a theoretical model that identified key factors influencing the effectiveness of museum communication.

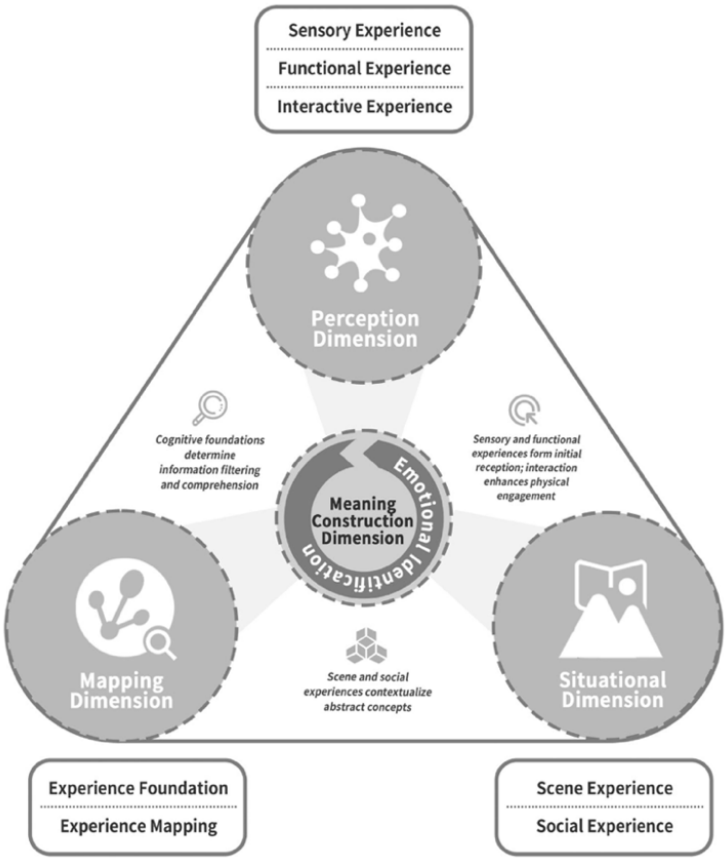


Figure 5: Factors affecting museum gamification's effectiveness in cultural heritage communication in Chen et al. (2025, p. 7)

It notes that success depends on activating the audience's bodily experience and fostering multi-sensory environments. In their model, the Perception Dimension, encompassing Sensory, Functional, and Interactive Experiences, represents the initial phase of information reception. Interactive Experience, including installation and personnel interaction, is key because it shifts passive observation to active participation, boosting bodily engagement. This ultimately facilitates the Meaning Construction Dimension, centred on Emotional Identification, which transforms these experiences into internalised cognition through a sense of achievement and empathetic design.

To achieve an interactive experience, the physical object must be connected to digital content through multi-modal feedback. Both Theodoropoulou et al. (2022) and Marshall et al. (2016) support the strategy of triggering rich, personalised narratives via auditory and visual outputs to forge a stronger emotional connection. Marshall et al. (2016) demonstrated this by using physical replicas and glass vitrines to trigger auditory feedback, while Theodoropoulou et al. (2022) employed a virtual environment.

In an interview with the Curator for Education and Outreach at the Hunt Museum in Limerick (January 2026), the interviewee stated that to improve engagement, the exhibitions should leverage incentivised learning and multi-sensory outputs. Providing these multi-sensory outputs is essential for neurodivergent visitors and those with disabilities.

> *“I think it's definitely a combination without question. We all learn in very different ways. So giving people option, giving people options is really, really important.” (Cagney, 2026)*

The research project presented in this paper uses tactile manipulation of a puzzle, auditory narration, and visual projection, blending these modalities into a unified embodied experience. This design directly supports the aim of making information accessible and tangible.

D'Agnano et al. (2015) further emphasise this point, arguing that the real value of such systems lies in their ability to transform passive displays into active learning tools.

> *"The system consists therefore in the realisation of a technology that transforms mute replicas of a work of art in speaking models, integrating the direct tactile experience with the fruition of localised audio content.” (D’Agnano et al. 2025, p. 208)*

The emphasis on tangible and embodied interaction is also a deliberate strategy to address the limitations of purely digital interfaces. Damala et al. (2016) suggest that tangible and embodied methods can address problems caused by screen-based devices, which might disengage visitors from the objects' materiality and the physical experience of the visit. Their work demonstrates the practical value of encouraging a deeper multisensory engagement with artefacts. They note that measuring the impact of new technologies, particularly those involving tangible and embodied interaction, is one of the main challenges identified in the 2015 NMC Horizon Report. This underscores the necessity of devising robust audience research to "document, analyse, and interpret the impact of digitally enhanced, tangible, embodied, and multisensory" (Damala *et al.* 2016, "Abstract") technology when integrated with physical exhibits. Ultimately, the combination of tactile manipulation with immediate, logical auditory and visual feedback has been shown to create a richer, more memorable learning experience.

2.2 Technological Foundations for Smart Replicas

2.2.1 3D Printing: Materials, Processes, and Costs

Three-dimensional (3D) printing is a rapidly evolving field with nearly unlimited potential. It began developing as an industry in the 1980s. However, this technology was initially only accessible to professionals due to its high cost (Canessa *et al.*, 2013). This changed when the Fused Deposition Modelling (FDM) patent expired around 2009 (Canessa *et al.*, 2013). The FDM manufacturing technique uses "the principle of creating a body by successively placing layers of material on top of each other" (Andronov *et al.* 2023, p. 1).

In FDM, the fused material is deposited as a filament onto a printing bed (Andronov *et al.*, 2023). These filaments melt at temperatures between 170 and 250 degrees Celsius to form multiple layers, thereby producing a 3D-printed object (Canessa *et al.*, 2013). Due to its simplicity and low cost, this method is particularly popular with hobby printers and is primarily used to produce prototypes and concept models (Andronov *et al.*, 2023). The widespread adoption of FDM is further supported by the open-source movement, which facilitates the free sharing of 3D-printable files and designs (Canessa *et al.*, 2013). The proposed research uses multiple open-source files.

PLA, or Polylactic acid, is recognised as the most widely used printing material (Andronov *et al.*, 2023). PLA is a biodegradable plastic made from corn starch and is partly recyclable. It is popular due to its non-toxicity, low cost, and ease of printing, as it does not significantly shrink during cooling, thereby maintaining dimensional accuracy (Andronov *et al.*, 2023). This is particularly important in the context of the proposed research. Furthermore, Stecuła et al. (2024) found that compared with ABS, Acrylonitrile Butadiene Styrene, PLA exhibited a higher tensile strength, making it more durable. It also found that larger layer heights increased breakage within those layers, suggesting that smaller layer heights could further improve durability (Stecuła *et al.*, 2024). This and the increased detail are the reasons why this research uses a layer height of 0.12 mm, the second-smallest available on the Bambu A1 mini printer. The cost of PLA today is about 20 EUR per kilo. A kilo of filament can roughly print four 27-cm Caryatid replicas, making it cost-effective.

In 2013, printers cost between 300 and 1,500 USD, making the technology accessible across a range of budgets (Canessa *et al.*, 2013). Since 2013, 3D printers have become even more pop-

ular and affordable, with the Bambu Lab A1 Mini used in this research costing 189€. The main limitation of 3D printing is the reduced dimension available due to the size of the printing bed. However, large objects can be printed in segments and then assembled (Canessa *et al.*, 2013), as done by Bonora et al. (2021).

Crucially, material selection must balance the museum's practical constraints with visitor expectations. Wilson et al. (2018b) evaluated touchable 3D-printed replicas and identified three main factors that influence visitor preference: Verisimilitude (realism and detail), Robustness (strength, durability, weight), and Quality (strength, perceived expense). Their findings indicated that Verisimilitude is the most important factor in visitor preference, with visitors valuing clarity and resemblance to originals more than robustness. Furthermore, visitors most preferred painted, clear, and white resin, whereas colour sandstone, blue plastic, and stainless steel, despite their durability, were least preferred. While Wilson et al. (2018b) found painted resin was most preferred, the current research budget and sustainability objectives necessitate the use of PLA to meet the cost and ease-of-replacement demands identified by Marshall et al. (2016). However, a marble-like PLA is utilised to balance the realism criteria outlined above and budget constraints.

Andronov et al. (2023) reported similar findings in a detailed techno-economic analysis of PLA for FDM. Their study showed that, contrary to the common belief that higher prices correlate with better quality, the second-cheapest PLA exhibited the best overall quality and mechanical properties. This evidence provides strong justification for prioritising cost-effective PLA while acknowledging the need to optimise quality to maximise engagement.

Test/Manufacturer	Prusament	Devil Design	Sunlu	C-Tech	Verbatim	Tronxy	Plasty Mladeč	Gembird
σ_m—wires	3	8	1	7	2	5	6	4
σ_m X-axis	2	8	5	7	1	6	4	3
σ_m Y-axis	5	8	1	6	2	3	7	4
σ_m Z-axis	8	3	2	6	5	4	7	1
Stringing	8	6	1	3	4	2	7	5
Overhang quality	5	3	1	8	6	7	2	4
Composability	8	2	5	3	4	1	7	6
Stringing pins	2	6	5	7	4	8	1	3
Pins	3	8	1	5	5	7	2	6
Holes	8	1	8	5	5	3	8	2
Pin height	6	8	6	2	6	1	8	6
Overhang angle	5	4	1	8	3	2	6	7
Sum	63	65	37	67	47	49	65	51
Ranks	**4**	**2**	**8**	**1**	**7**	**6**	**2**	**5**
Price [1] (EUR)	23.44	19.95	14.12	16.20	24.69	18.00	23.44	17.25
Price (EUR)/point	0.372	0.305	0.383	0.243	0.524	0.368	0.360	0.336
Ranks price/point	**6**	**2**	**7**	**1**	**8**	**5**	**4**	**3**

[1] Prices valid for Q3/2022.

Figure 6: Evolution of results of a techno-economic evaluation of PLA materials in Andronov et al. (2023, p. 17)

Another factor to consider is that the accessibility of 3D-printed replicas is not solely dependent on the printing hardware. While traditional digitisation methods were often slow and required expert knowledge, recent advancements in “Gaussian Splatting” have made creating digital replicas more accessible. Dahaghin et al. (2024) propose a pipeline that enables the 3D digitisation and segmentation of museum artefacts using standard smartphone RGB imagery. Their “Gaussian Heritage” approach reduces the financial and technical barriers to institutions digitising their collections, providing a scalable pre-processing step for the FDM printing processes discussed in this research. This shift toward affordable, smartphone-based digitisation mirrors the democratisation of manufacturing brought about by the expiration of FDM patents, collectively enabling a more sustainable ecosystem for museum interactives.

This trend toward cost-effective digitisation is further supported by the work of Bonora et al. (2021), who successfully utilised Structure-from-Motion (SfM), an image-based photogrammetry technique, to create high-resolution digital replicas of marble statues. By leveraging standard digital photography and automated surface reconstruction, their workflow provided an accurate, low-cost alternative to active range-based sensors, such as laser scanners, while maintaining the metric precision required for full-scale 3D printing.

2.2.2 Laser Cutting: Material, Processes, Costs and a Comparison to 3D Printing

Laser Cutting is a long-established manufacturing process that utilises a subtractive method to create precise 2D shapes from sheets of material. Developed in the 1960s, with one of the first machines created by the Western Electric engineering Research Centre in 1965, the technology has evolved from a heavy-industry tool into a cornerstone of rapid prototyping. Unlike FDM 3D printing, which builds objects layer-by-layer, laser cutting uses a high-powered laser beam to cut a variety of shapes along a predetermined vector path from different sheets of material. This process is highly valued for its speed and high production volume, as it can cut shapes from sheet material in a few seconds (McClements, 2022; *Laser Cutter vs 3D Printer: Which Technology Is Right For Your Manufacturing Needs?*, 2024).

A primary challenge in laser cutting is the transition from 2D planar components to 3D structural forms. This is typically achieved through specialised joinery techniques, most notably "finger joints" (Tobon, 2022). This method involves cutting interlocking rectangular tabs along

the edges of connecting panels, thereby increasing the surface area for bonding and providing mechanical stability without relying solely on heavy adhesives (Tobon, 2022; *Laser Cutting Box Design: Your 7-Step Perfect Fit Guide*, 2025).

A critical technical consideration in the laser cutting process is kerf, the width of material removed by the laser beam. Because a laser beam has a physical diameter, it does not create a zero-width cut. Instead, it vaporises a small portion of the material (*Laser Cutting Box Design: Your 7-Step Perfect Fit Guide*, 2025). This needs to be considered when designing vector drawings for laser cutting as part of the proposed research.

The choice of material is as critical in laser cutting as it is in 3D printing. The most common materials for laser cutting include plywood, Medium-density fibreboard (MDF) and Acrylic (*Laser Cutting Box Design: Your 7-Step Perfect Fit Guide*, 2025). Plywood is frequently selected for its durability. Acrylic, on the other hand, offers a modern, clean look and a wide range of colours and transparencies. MDF is the most budget-friendly material and offers a smooth finish because it is a composite wood product. It lacks a natural grain and behaves uniformly when cut, which reduces the risk of warping or splintering compared to plywood (*Laser Cutting Box Design: Your 7-Step Perfect Fit Guide*, 2025). This proposed research uses MDF due to its availability and its ability to hide the technology that is kept inside the laser-cut base.

Comparison and Complementary Application

The decision to employ either 3D printing or laser cutting depends on the required design/geometric complexity, production volume, material requirements, time constraints and the physical scale of the component.

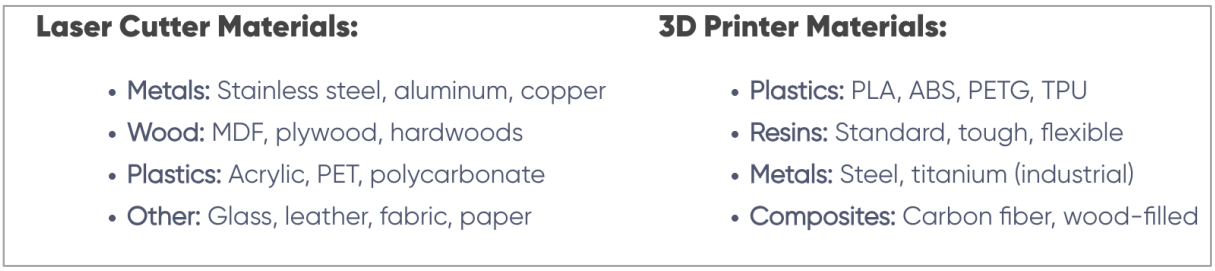


Figure 7: Laser Cutting and 3D Printing Materials in in *Laser Cutter vs 3D Printer: Which Technology Is Right For Your Manufacturing Needs?* (2024, "What Materials Can Each Technology Process?" section)

3D printing is the superior choice for objects requiring high geometric complexity, such as organic forms or detailed replicas with internal features that would be impossible to fabricate

through subtractive means (*Laser Cutter vs 3D Printer: Which Technology Is Right For Your Manufacturing Needs?*, 2024). 3D printing is a low-waste process. However, it is significantly slower and typically limited to smaller build volumes.

Conversely, laser cutting excels in production efficiency and scale. It is the preferred method for creating large-scale structural enclosures or flat-packed components, as it can process large sheets of material in a fraction of the time required for an equivalent 3D print (*Laser Cutter vs 3D Printer: Which Technology Is Right For Your Manufacturing Needs?*, 2024). While laser cutting is limited to 2D geometries, joinery techniques enable the construction of 3D objects. Ultimately, these technologies are often complementary rather than competing.

Attributes	3D Printing	Laser Cutting
Machine cost	$250 to $350,000+	$1,000 to $45,000+
High production rate	No	Yes
Uses laser energy source	Yes (SLS, DMLS)	Yes
Can produce sheet metal parts	No	Yes
Can produce complex 3D parts without additional steps	Yes	No

Figure 8: 3D Printing and Laser Cutting Properties in Comparison in McClements (2022, "Comparison Table Between 3D Printing and Laser Cutting" section)

2.2.3 Physical Computing

The functionality of Tangible Smart Replicas (TSR) is fundamentally dependent on a well-justified physical computing infrastructure. This infrastructure needs to facilitate the visitors' input and the system's digital output. The two essential components in this infrastructure are the microcontroller for control and the sensing mechanism for interaction (Wong *et al.*, 2015).

The system proposed in this research relies on two technologies for its operation. The first is Near Field Communication, or NFC. This is a short-range, low-power wireless communication protocol that enables data exchange between two electronic devices. The two devices are typically a reader and a passive tag (Razak *et al.*, 2024). NFC is considered a reliable, low-cost,

non-visual technology used primarily to provide precise identification and spatial location on a physical surface (D'Agnano *et al.*, 2025). The second key technology used in the proposed research is the Arduino, an open-source electronics platform based on an easy-to-use single-board microcontroller. The Arduino is primarily designed for high-reliability, real-time control applications, making it ideal for managing low-level input/output and directly interacting with sensors (Mahdi *et al.*, 2022).

The choice of the Arduino as the central control hardware is based on a critical trade-off analysis between microcontrollers and microcomputers performed by Mahdi et al. (2022). In their study, they found that a microcomputer, such as the Raspberry Pi, offers superior processing power and larger RAM, both of which are necessary for managing complex multimedia and running a full operating system. However, the Raspberry Pi is not as efficient for direct, low-latency Input/Output control. Its system requires more power and is therefore more affected by power outages than its competitor, the Arduino (Mahdi *et al.,* 2022). The Arduino's simpler, embedded architecture is ideal for low-level Input/Output and real-time control. It provides a high reliability, low power consumption and cost-effectiveness necessary for simple, stable, and long-term museum installations (Mahdi *et al.*, 2022).

The suitability of the Arduino platform is further validated by Wong et al. (2015). In their work, they demonstrated that interactive features could be effectively implemented in traditional museum environments that "lack technical infrastructure" (Wong *et al.* 2015, p.1). The Arduino Uno was chosen for "its ability to manipulate devices and its well-developed open-source library" (Wong *et al.* 2015, p. 2) and its capability to link hardware with digital outputs. This provides an important use case that cultural heritage institutions can utilise when implementing microcontrollers at scale (Wong *et al.*, 2015).

Complementing the Arduino's control capabilities, Near Field Communication was selected as the primary sensing method to facilitate tangible interaction. The use of embedded NFC readers and tags has been shown to be a reliable method for triggering digital content. This approach has been effectively utilised in smart replicas to reliably activate digital audio content, thereby supporting its application in interactive museum exhibits (Marshall *et al.*, 2016). Furthermore, NFC technology has been shown to support accurate spatial interactions, as demonstrated by D'Agnano et al. (2015). Their system employs a smart ring interacting with a tactile surface embedded with NFC sensors to deliver localised audio feedback. These studies

confirm that combining the Arduino for stable Input/Output management with NFC for precise, non-visual input, on a robust physical computing foundation, is essential for the TSR developed in the proposed study.

Lastly, in an interview with the Curator for Education and Outreach at the Hunt Museum in Limerick (January 2026), Cagney stated that, since museums often lack internal technologists, electronics must be standard and readily available to avoid long shipping delays or out-of-order exhibits due to a lack of easy-fixing solutions. She said, “Yeah, we've had very positive experience overall with NFCs” (Cagney, 2026). This further justifies the use of low-cost and open-source electronics.

2.2.4 Longevity and Sustainability of 3D Printed Replicas

The viability of Tangible Smart Replicas (TSR) as an exhibit ultimately depends on their operational longevity and material sustainability. The selection of 3D printing technology addresses both. McDermott et al. (2014) confirm that the most significant barrier to the long-term success of interactive digital exhibits is not technological failure, but operational failure rooted in staff capacity and maintenance concerns. They state that, especially in small and medium-sized museums, with no more than 50 staff members, staff lack the necessary technical skills to implement and maintain complicated digital exhibits. Implementing these exhibits can lead to a variety of problems, such as confusing navigation and controls, broken exhibit components, and usability issues, resulting in a disappointing museum experience for visitors. This foundational constraint mandates that any new system must prioritise simplicity, reliability, and cost-effectiveness. This will mitigate the risk of out-of-order installation components and poor maintenance.

The decision to use Fused Deposition Modelling (FDM) is a strategic response to this operational reality. The low cost and repeatability of FDM align with the toolkit approach proposed by Marshall et al. (2016). This shifts maintenance capabilities from reliance on external experts to empowering in-house staff. That ease of replacement is paramount is further reinforced by the material selection. While visitors prefer materials such as resin, long-term operational needs require durability for frequent handling, justifying the choice of Polylactic Acid (PLA) over high-detail alternatives (Wilson *et al.*, 2018b). PLA is a suitable thermoplastic that yields a robust final replica and is easily replicated. The potential of low-cost 3D printing in the cultural heritage sector has been established since at least 2014 (Cooper, 2019). Moreover, the

development of Tangible Interaction as a well-established research area over the past two decades proves that smart replicas are not merely a passing technological trend. Instead, they represent a mature and enduring approach to visitor engagement and display design, emphasising the long-term pedagogical relevance of the TSR approach (Duranti et al., 2024).

The use of FDM and PLA is further supported by Bonora et al. (2021) as a robust solution for large-scale replicas. In their study, they found that while FDM printing results in visible layer lines, the material's structural durability and cost-effectiveness make it ideal for exhibits intended for physical interaction or outdoor display. However, they emphasise that the longevity of such replicas depends not only on the printing material but also on protective coatings that shield the underlying thermoplastic from UV radiation and environmental wear. This reinforces the argument that robustness cannot be ignored when creating high-fidelity visual detail.

From an environmental standpoint, the choice of material is further supported by the work of Ibrahim et al. (2024) and Canessa et al. (2013). As mentioned previously, PLA is a biodegradable plastic derived from renewable sources such as corn starch. 3D printing is generally considered more sustainable than traditional manufacturing processes, as objects use only the material they require rather than large amounts of material that must be trimmed in post-production (Canessa *et al.*, 2013). Additionally, recycled PLA has been an increasingly studied topic. Ibrahim et al. (2024) describe the established process of utilising waste plastic, such as discarded prints or packaging, through Additive Manufacturing (AM), demonstrating the technical feasibility of a closed-loop system for museums to reprocess their own plastic waste into new filament.

The use of recycled plastic feedstock to produce filament is reported to offer a substantial cost reduction compared to using commercial virgin filaments, further reinforcing the long-term economic sustainability argument first raised by Marshall et al. (2016) (Ibrahim *et al.*, 2024). While recycled filaments can exhibit slightly lower mechanical properties, such as tensile strength, than virgin material, Ibrahim et al. (2024) note that the resulting prints are often sufficient for non-load-bearing applications, such as museum replicas, where durability for handling is key but structural integrity is not a primary concern.

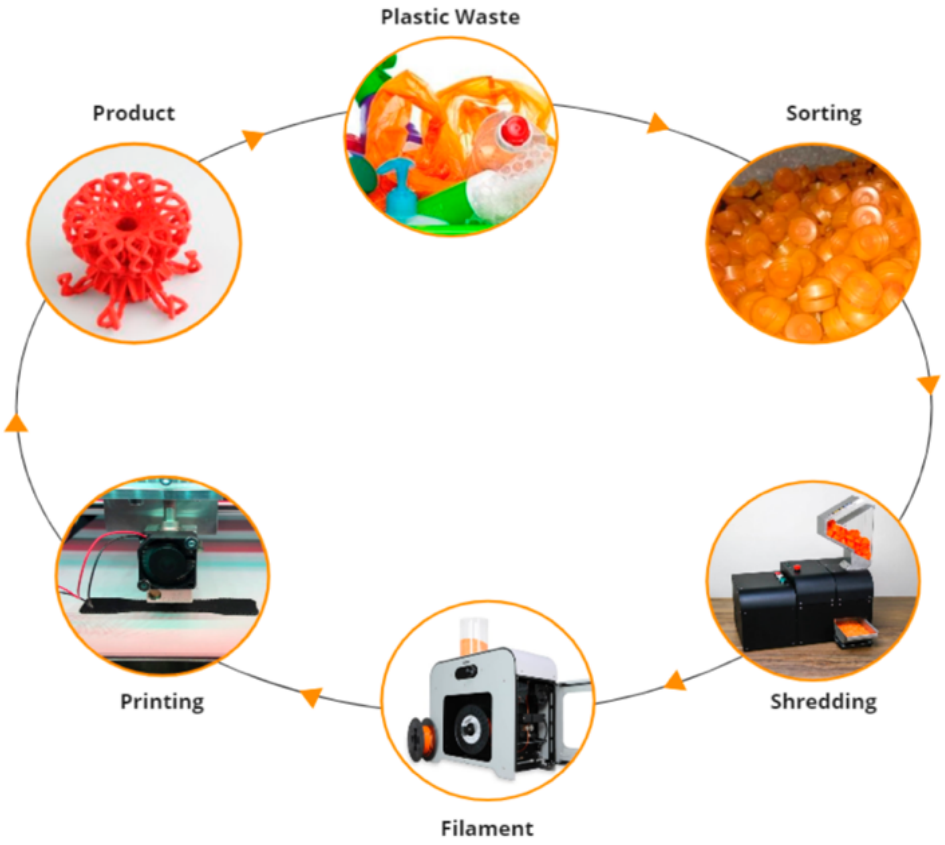


Figure 9: Schematic for waste plastic recycling through AM in Ibrahim *et al.* (2024, p. 3)

For long-term viability, the creation process must move toward a practice-based model. Petrelli et al. (2016) suggest that "Museums are more used to a traditional progression centred on decision making instead of prototyping and experimenting. In our experience, it is important to engage in a practice-based creative process, possibly in the safe environment of a prototype trial. This builds up confidence in the team and trust." (Petrelli *et al.*, 2016, p. 9). They accomplished this by having the designers, technologists and curators work closely together. The designers and technologists implemented and tested the interactive exhibit. The curators developed the content and materials for the exhibit. This methodology ensures the museum staff feel a sense of ownership over the final installation.

2.3 Evaluation Metrics

This chapter establishes the foundations of the project's methodology by reviewing and synthesising the evaluation metrics used in the relevant literature. By examining the evaluation metrics used in prior studies, this review provides the rationale for the specific acceptance criteria and hypotheses employed in this project's methodology.

2.3.1 Visitor Engagement and Enjoyment

The core aim of Tangible Smart Replicas is to reverse the "DO NOT TOUCH" (Wilson *et al.* 2018a, p.1) barrier and encourage memorable experiences (Wilson *et al.*, 2018a).

Wilson et al. (2018a) used interviews conducted after visitors' interactions with the replicas to measure visitor enthusiasm and willingness to revisit.

Marshall et al. (2016) logged data gathered from the technology itself, observations of visitors while engaging with the TSRs, and semi-structured interviews with visitors after the interaction. This approach demonstrated the utility of combining subjective interview data with objective data from data logging to assess engagement depth.

Pallud (2017) used a field study and cross-sectional surveys to validate her hypothesis. The author notes that a longitudinal design would have been more suitable, but it wasn't feasible due to the inability to monitor visitors over time. This highlights the limitations in evaluation methods when working with museum visitors.

Pattakos et al. (2023) utilised the Heuristic Evaluation method with experts and user testing with co-workers to evaluate the usability of their interactive display case. This supports the use of experts and user feedback to assess the interaction experience.

Petrelli and O'Brien (2018) used a 7-point Likert-scale questionnaire, open-ended questions on likes and dislikes, multiple-choice questions, and observations to evaluate three interaction modes in the same exhibit.

Liao et al. (2025) utilised a quasi-experimental pretest–posttest design. They divided their 20 participants into an experimental group and a control group. Each group was presented with the same quiz after their learning session. Their approach validates both the sample size and the use of a control group for testing this research's prototype.

Marshall et al. (2015) employed a combination of physical dwell time, measured via proximity sensors, and digital interaction via Twitter to measure visitor interest in exhibits. This approach supports this project's evaluation of dwell time and its use as a measure of enjoyment.

Schou and Løvlie (2020) utilised observations to investigate visitor engagement after redesigning and including a TSR in their exhibit, further supporting the approach of observations.

Wacker et al. (2016) employed a “between-groups” field study in which groups were assigned one of three technologies. The participants’ interactions were logged further validating the use of groups for testing.

As these studies successfully evaluated their replicas based on visitor engagement and enjoyment, this study employs a semi-structured interview approach combined with Likert scales. Furthermore, a user testing session will be conducted in which the tester will be observed.

2.3.2 Visitor Recall (Cognitive Impact)

Tangible Smart Replicas must move beyond enjoyment to demonstrate their pedagogical value, showing that tangible interaction aids the retention of cultural heritage information.

Alt et al. (2013) measured users' recall and recognition post-interaction using free-recall tests and Likert scales assessing their confidence that they had previously seen an item. A free-recall test requires users to reproduce items they had previously seen. This robust method is crucial for obtaining objective data.

As previously noted, Pallud (2017) used a cross-sectional survey to test her hypothesis regarding learning experiences in museums, including recall and enjoyment. The paper primarily assessed perceived learning outcomes rather than objective knowledge retention.

As previously mentioned, Liao et al. (2025) utilised a pretest–posttest design to test the knowledge increase in their participants.

Given the successful evaluation of these papers, this proposed research employs a post-interaction knowledge test, in the form of a survey, to assess visitors' recall.

2.3.3 Practicality and Usability for Long-Term Museum Integration

The technical and operational viability of the Interactive Exhibit for long-term use by museum staff and visitors is essential to its long-term integration.

McDermot et al. (2014) use interviews with museum staff to evaluate the challenges and opportunities they face in designing interactive exhibits.

As noted earlier, Pattakos et al. (2023) use expert heuristic evaluations and user testing to assess usability and practicality. This mixed-method approach is essential for identifying both expert-level design flaws and general user difficulties.

Liao et al. (2025) and Wacker et al. (2016) utilised the System Usability Scale to evaluate the usability of their experiences. This offers a quantifiable result on usability.

Given the scope of this project, the methodology for evaluating practicality and usability for long-term museum integration will be a semi-structured interview with a local museum expert. Additionally, a user testing session will be conducted, and a System Usability Scale questionnaire will be administered to assess practicality and usability further.

2.3.4 Sustainability of 3D-Printed Replicas

Sustainability in this context is defined by cost-effectiveness, material durability and long-term operational viability.

Wilson et al. (2018a) used semantic differential scales to assess visitors' perceptions of the replicas' visual and haptic properties, including texture, realism, and durability.

There is a lack of further documentation on the evaluation of the long-term sustainability of 3D-printed replicas in museums. Therefore, this research introduces its own evaluation metrics, as outlined in the methodology chapter.

2.4 Summary of State of the Art & Research Gaps

This chapter summarises the findings of the literature review to define the existing state of the art in Tangible Smart Replicas, identify current research gaps and position this project as a novel contribution to the field.

The State of the Art confirms a strong shift in cultural heritage from a "Glass-case" (Wilson *et al.* 2018a, p.1) paradigm toward facilitating multisensory, embodied experiences (Marshall *et al.*, 2016; Pallud, 2017; Wilson *et al.*, 2018a). Furthermore, the use of Tangible Smart Replicas is conceptually mature and has been a sustained area of research for over two decades (Duranti *et al.*, 2024). This confirms its relevance as a non-fleeting approach in engagement.

The existing research also establishes that low-cost, open-source physical computing platforms, such as the Arduino and NFC, are proven, robust solutions for low-infrastructure museum environments (Wong *et al.*, 2015; Mahdi *et al.*, 2022). It also offers the main justification for material and technical simplicity. The operational realities among Cultural Heritage Profes-

sionals reveal technical knowledge gaps that necessitate low-cost replacements and high reliability as non-negotiable design priorities (McDermott *et al.*, 2014; Marshall *et al.*, 2016).

The review and synthesis of the existing literature have revealed four gaps that this research project addresses. The first gap is the integrated system evaluation. Much research focuses on either technical feasibility (D'Agnano *et al.*, 2025) or visitor attitude (Wilson *et al.*, 2018b). There is a research gap in comprehensive assessments of the long-term, low-cost technical solutions offered by Arduino and 3D printing, as well as of measurable visitor enjoyment and recall. The second gap concerns staff-centric longevity metrics.

While Petrelli et al. (2016) demonstrate the power of "co-design" and "co-creation" between curators, designers, and technologists to create immersive, multi-perspective narratives, there remains a gap in establishing standardised, sustainable workflows that allow museum staff to independently manage and update these complex, content-driven tangible systems beyond the initial collaborative design phase. Their work highlights that while smart replicas can successfully foster emotional engagement and "meaning-making" through contrasting personal stories, the long-term success of such installations relies on a leap of faith in technical reliability in "hostile" museum environments.

McDermott et al. (2014) identify the third gap in the research, the technical knowledge gap. A significant limitation in the literature is the lack of evaluations of the true maintainability of these exhibits for staff. The concept of toolkits is well established (Marshall *et al.*, 2016), but formal metrics for ease of repair and replacement by non-technical staff are often lacking.

The last gap involves further integration of NFC technology. Although NFC has been validated for content triggering (Marshall *et al.*, 2016), there is a gap in assessing the specific effectiveness of using multiple NFC localisation points to drive different narratives within a 3D form.

This project addresses these gaps by developing a fully integrated system designed specifically for staff practicality and low-cost production, directly tackling the constraints identified by McDermitt et al. (2014). Furthermore, this project utilises a puzzle-based interaction to increase engagement and recall, and employs NFC localisation to deliver sequential, multi-part narratives effectively. It thereby moves beyond simple content triggering. Lastly, it establishes acceptance criteria in the methodology chapter, justified by both technical usability and ped-

agogical metrics, to support integrated system evaluation, which is currently lacking in the state of the art.

2.5 Key Takeaways

The literature review provides several critical considerations that must inform the design and planning of the Tangible Smart Replica and its subsequent evaluation.

Content is Key

The ability to touch a replica alone is insufficient. The Tangible Smart Replica must provide engaging and complementary digital content related to the original object, supporting it without distracting from the experience, to ensure that the replica is considered a successful digital replica of the original (Wilson *et al.*, 2018a).

Prioritise Robustness over Fidelity

Longevity is achieved through ease of replacement and durability rather than high-fidelity visual detail. The use of PLA and FDM technology is a validated trade-off that addresses high visitor handling and the need for cost-effective maintenance (Marshall *et al.*, 2016; Wilson *et al.*, 2018a; Wilson *et al.*, 2018b).

Design for Museum Staff

The design must be simplified to account for the lack of in-house technical personnel. The use of the Arduino's simple architecture and the toolkit approach presented by Marshall et al. (2016) is non-negotiable for long-term viability (McDermott *et al.*, 2014).

Validate Usability Early

Technical acceptance must be tested alongside educational outcomes. The evaluation must include a robust method to ensure that the physical computing system is easy to use. Otherwise, the exhibit risks disappointment and failure (McDermott *et al.*, 2014; Razak *et al.*, 2024).

Interaction Must Be Meaningful

The tactile experience must move beyond simple observation. The Tangible Smart Replica must leverage the physical engagement to create an enjoyable and memorable experience that simulates learning and curiosity (Wilson *et al.*, 2018a; Wilson *et al.*, 2018b).

3 Methodology

This chapter explores the research methodology employed to design, develop and evaluate the Tangible Smart Replica of an Ancient Greek statue. The core of this research is a Design-and-Development approach that bridges the theoretical understanding of museum interactivity and the development of a working prototype.

The research is structured into three phases: Exploration and Contextualisation, Prototyping and Fabrication, and Evaluation and Reflection. This approach bridges the theoretical concepts of embodied cognition and tangible interaction, identified in the previous chapter, with the practical creation of a functional, testable and sustainable prototype. Lastly, this chapter will detail the acceptance criteria used to assess project success and the ethical framework that guided the evaluation with human participation.

3.1 Project Structure

The research was divided into three main phases:

1. Exploration and Contextualisation (Phase 1): This phase defines the requirements for the project's digital fabrication and interaction components, informed by the literature review. It also details the design iteration process.
2. Prototyping and Fabrication (Phase 2): This phase implements the design using 3D printing, laser cutting, hardware integration and software development.
3. Evaluation and Reflection (Phase 3): This phase tests the Tangible Smart Replica with users and analyses its effectiveness in improving visitor engagement and recall, as well as its sustainability and practicality for long-term museum integration.

3.2 Phase 1: Exploration and Contextualisation

3.2.1 Objectives and Hypotheses

The primary objective of this research is to design, develop and evaluate a Tangible Smart Replica of one of the Caryatids, structured as a 3D puzzle. This replica shall enhance visitor engagement in a museum setting and be sustainable and practical for long-term integration.

This objective is measured by testing the following hypotheses:

H1 (Engagement): Interactivity achieved through the assembly and placement of the smart replica significantly increases visitor enjoyment in a museum context compared to a traditional static display.

H2 (Recall): Interactivity achieved through the assembly and placement of the smart replica, supported by an auditory and visual information display, significantly increases visitor recall in a museum context compared with a traditional static display.

H3 (Practicality): A 3D-printed replica constructed as a puzzle is practical for long-term integration in a museum environment.

H4 (Sustainability): A 3D-printed replica constructed as a puzzle is sufficiently durable and sustainable for long-term integration and repeated use in a high-traffic museum environment.

3.3 Phase 2: Prototyping and Fabrication

This chapter details the technical and practical methods employed to design, develop and evaluate the Tangible Smart Replica.

3.3.1 Digital Sculpting

This project utilises Meshmixer, a free Autodesk application that facilitates the cleaning of 3D scans through mesh editing. Due to its ability to edit meshes, Meshmixer is used to increase the wall thickness of the original model file and scale it down. This enabled the further design process in Blender. Blender is a free and open-source 3D creation software. This project primarily uses Blender to apply Boolean Operations to achieve the required segmentations for the puzzle design. Furthermore, the Boolean Operations are used to cut magnet-sized indents into the wall offset to allow the closing mechanism to be integrated once printed. Blender was also used to create frames and supports for the electronic components, such as the NFC reader. This allowed the readers to be positioned close to the lid and, therefore, able to read the tag inside the model.

This process uses two file formats. The downloaded model was originally an STL file. This file format represents the surface of a 3D object using a mesh of connected triangles and is the industry standard when sharing 3D prints. This file was modified into an OBJ file in Meshmixer.

The OBJ file format uses simple, plain text to define 3D geometry. OBJ was used because this file format supports complex polygons, materials, and textures. However, once the modifications were completed, the OBJ file had to be exported as an STL to ensure compatibility with BambuStudio.

3.3.2 Fused Deposition Modelling Fabrication

The physical realisation of the prototype was achieved through Fused Deposition Modelling (FDM). As established in the literature review, FDM melts filaments, which are then used to form multiple layers that, in turn, produce a 3D model. This method focuses on balancing verisimilitude with material sustainability by utilising Marble-like PLA (Polylactic Acid) filament. This project also uses white and black SUNLU PLA+ for the frames housing the electronic components, additional supports for the base lid, and additional informational signs. This material choice was selected over alternatives such as resin or ABS because PLA meets the aesthetic requirements for realism while remaining cost-effective and easy to replace in a museum context. Additionally, PLA is non-toxic and maintains dimensional accuracy during cooling, which is particularly important for this project. Previous literature highlights that the cost and ease of creation are paramount for long-term museum integration. The fabrication process includes fine-tuning slicing parameters, such as layer height and infill density, to ensure both surface quality and structural durability for public handling.

3.3.3 Laser Cutting and 2D Vector Drawing

The base used in this project was created using Laser Cutting. As established in the literature review, laser cutting uses a subtractive method to create precise 2D shapes from sheets of material. Laser Cutting was chosen for the creation of the base due to its size and required robustness. To accommodate the physical computing components and the replicated statue, the base needed to measure 60 x 30 x 10 cm. As the 3D printing bed measures 18 x 18 x 18 cm, the base would have had to be divided into at least four pieces, thus creating an unstable, subdivided base. Using laser cutting avoided this problem and additionally served as a time-saving method. Additionally, a box for the statue pieces was laser cut as the size requirements exceeded the printing bed dimensions.

The laser used for this project was the Epilogue Laser Fusion M2. The material chosen was a 6mm wood MDF. This material was chosen for its availability, and the thickness was deter-

mined to provide sufficient structural integrity to support the statue when placed on the lid. It also allowed engravings on the lid to help the user place the statue.

To create the file for the Laser Cutter, Affinity Vector was used. The base follows a U shape similar to the replica's original temple structure. 10 panels were used and attached to each other with finger joints and wood glue. The laser cutter used the default settings: a speed of 3%, a power of 100%, and a frequency of 10.

3.3.4 Physical Computing and Sensor Integration

The Tangible Smart Replica's digital outputs are implemented through physical computing. An Arduino Uno serves as the central processing unit, chosen for its robustness and open-source accessibility. The system allows museum staff to maintain it without constant external technical support.

The object detection method is implemented using Near-Field Communication (NFC) technology, specifically an Elechouse PN532 V3 module. As previously established, NFC is a short-range, low-power wireless communication protocol. It enables the data exchange between a tag and a reader. This project embeds an NFC tag within the replica and connects the readers to the microcontroller to recognise specific placements on a sensor-equipped base. NFC was selected as a more robust solution than visual or touch-detection systems, which often encounter issues with light reflections. This system triggers multimodal feedback, including auditory narration, a confirmation sound, visual animations and a green LED indicator. Such feedback provides an immediate, intuitive reward for successful interaction, which is a key component in fostering the curiosity and cognitive engagement necessary for effective informal learning.

3.4 Phase 3: Evaluation and Data Collection

3.4.1 Mixed-Methods Evaluation Framework

To validate the project's hypotheses and answer the research question, a mixed-methods evaluation approach is employed.

An A/B user testing session was conducted to measure the differences in engagement and information recall. To ensure a statistically sufficient sample size to detect a significant differ-

ence in cognitive impact, each group required a minimum of 10 participants. This size provides sufficient power to statistically analyse the quantitative quiz data. The recruited testers will be randomly divided into two groups:

Group A (Control): Participants interacted with a static replica and an accompanying information text. This group isolates the variable of the TSR's interactivity and digital outputs.

Group B (Test Group): Participants engaged with the Tangible Smart Replica by assembling the puzzle and triggering multimodal outputs alongside the same information text.

Phase 1 (A/B Testing & Knowledge Quiz & System-Usability-Scale)

Participants were introduced to their respective setups. Usability and interaction were evaluated through direct observation and time-logging during the interaction. Immediately afterwards, all participants completed a Post-Interaction Knowledge Quiz to objectively measure their recall. After the Knowledge Quiz, they were asked to complete the System Usability Scale, which consists of 10 questions.

Phase 2 (Semi-Structured Interview with Likert Scales Questions)

Following the quiz, participants took part in a semi-structured interview to assess their engagement, subjective recall, and enjoyment. A number of interview questions use Likert scales to gather quantitative data on enjoyment. The remaining questions will yield qualitative data, offering rich, contextual insights to explain the quantitative scores and to capture the perceived benefits and usability of the tactic and interactive experience. The interview questions can be found in the appendix.

Expert Interview

An expert interview provided targeted qualitative data to validate the design rationale for long-term viability and address the crucial constraints of the museum environment.

A semi-structured interview was conducted with a local museum professional. The interview focused on assessing the TSR's practicality and sustainability from an institutional perspective. It covered themes such as economic viability and provided subjective validation of the project's €200 unit-cost criteria as a reasonable and sustainable investment for long-term integration. The interview questions can be found in the appendix.

3.5 Acceptance and Evaluation Criteria

To determine whether this research project has been successful, it is essential to define acceptance criteria clearly. This research follows a two-pronged evaluation: user-centric (engagement and recall) and technical (long-term practicality and sustainability).

TABLE 1: ACCEPTANCE CRITERIA

Criteria	**Acceptance Metric**	**Measurement Method**	**Hypothesis Connection**
Visitor Engagement	Recall: Participants who interacted with the prototype score better on the post-interaction knowledge quiz than participants who were presented with a static replica. Enjoyment: Mean rating for enjoyment of the interaction is 4.0 or higher on a 5-point Likert scale.	Knowledge Quiz Interview	H1 H2
Long-Term Museum Integration	Practicality/Usability: The System-Usability-Scale (SUS) is above 80.3. The 3D printed replica is considered practical for long-term integration and sustainable by the Curator for Education and Outreach of the Hunt museum, Maria Cagney. Sustainable Integration: The total cost of materials and fabrication for one unit is below €200 (excluding cost to purchase a 3D printer & laser cutter).	SUS Expert Interview Cost Breakdown	H3 H4

3.5.1 Itemised Project Requirements and Resourcing

TABLE 2: ITEMISED PROJECT REQUIREMENTS AND RESOURCING

Category	Component	Specification	Acceptance Criteria
Hardware	Microcontroller	Arduino Uno (1)	H3: Low-cost, reliable
		Breadboards (2) Cables (roughly 100)	
	Sensing	NFC Readers (PN532) (6) NFC tag (1)	H1: Enable interaction and content triggering
	Output	Projector/Screen with integrated speakers (1) LEDs (6) LED holders (6)	Multi-Modular feedback system
	3D Printer	Bambu A1 mini (1)	
	Laser Cutter	Epilog Laser Fusion M2 (1)	
Materials	3D Model	Copy of Caryatid C from MyMiniFactory (1)	High-detail, open-license model
	Filament	PLA Marble (250g) SUNLU PLA+ (Black & White) (390g)	H4: Low-cost and high durability
	Magnets	4x2mm magnets (100)	Secure, low-profile connection mechanism
	Wood MDF	6 mm 500x800 panels (3)	H4: Low-cost and high durability

	Fixings	Hot Glue Gun (1) Hot Glue Gun Sticks (6) Superglue (1) Wood Glue (1)	H4: Low-cost and high durability
Software	3D Modelling/ Editing	Meshmixer Blender	Modification of the model
	Slicer & Program-ming	BambuStudio Arduino IDE Processing	Print preparation and microcontroller logic
	Vector Drawing	Affinity Vector	Free vector drawing soft-ware
Resourcing/ Constraints	Economic	Cost of materials and fabri-cation	H4: Below €200

3.6 Practical Considerations

The project will be executed under strict constraints which directly inform the technical stack.

TABLE 3: PROJECT CONSTRAINTS AND MITIGATION STRATEGIES

Constraint	**Mitigation Strategy**	**Link to Criteria**
Economic Cost	Limiting the unit cost to below €200 by us-ing low-cost materials (PLA) and open-source hardware (Arduino Uno).	Sustainability (H4)
Technical Expertise	Use of the Arduino open-source platform and a simple modular design.	Practicality (H3)

Interactive exhibits are susceptible to failure due to public handling, wear and tear, and component malfunction. Anticipating and migrating these points is essential for validating the TSR's practicality and usability.

TABLE 4: POTENTIAL POINTS OF FAILURE AND MITIGATION

Potential Failure Point	**Mitigation Strategy**
Puzzle Piece Loss or Damage	The modular design allows for reprinting of individual segments using the established 3D printing files, rather than replacing the entire replica. The use of low-cost materials offers the opportunity to keep two statue replicas at the exhibit.
Magnet Failure or Loss	Magnet indents were designed to accommodate super glue, and the specific magnets are low-cost, bulk purchase item.
NFC Reader Failure	The design uses low-cost, replaceable NFC modules. The system is wired directly to the Arduino, avoiding complex network configurations. The Arduino code performs Health-Check allowing the system to self-reset if needed. All cables are glued to the Breadboards to minimise the chance of lose cables.
Arduino Processing Error	The code includes robust error handling to prevent crashes. An external, easily accessible hardware reset button is integrated in the Arduino Uno, allowing museum staff to reset the system instantly without needing technical expertise or access to the code.
Loss of Sound	All audio connections will be securely mounted. Furthermore, the information text accompanying the exhibit serves as a redundant visual option, ensuring the history and function of the Caryatids is still accessible to visitors.

3.7 Project Timeline

TABLE 5: PROJECT TIMELINE

Phase	Description	Timeline
Phase 1	Exploration and Contextualisation (Design Specification, Technical Stack Selection, Requirements Itemisation)	Completed. (30/01/26)
Phase 2	Prototyping and Fabrication (3D Modelling, Slicing, Printing, Electronic Integration)	Completed. (10/03/26)
Phase 3	Evaluation and Data Collection (A/B Testing, Expert Interview, Data Analysis)	Completed. (02/04/26)

3.8 Ethical Considerations

Ethical approval for this research has been granted by the Faculty of Science & Engineering Research Ethics Committee (S&E REC) at the University of Limerick. The ethical framework ensures the protection, privacy, and rights of all participants involved in Phase 3.

All participants were provided with a detailed information sheet and signed a Research Ethics Informed Consent Form before their involvement. This form explicitly outlines the nature of the study, the participant's role and how the collected information will be used.

Participation in this study is strictly voluntary. Participants are fully informed of their right to withdraw at any point during the study. The right to withdraw consent extends for up to two weeks after data collection is completed.

All participants remained anonymous throughout the study. No personal or identifying information was collected. Additionally, all participants received a unique identification code (e.g., P01, P02) for referencing in data analysis and reporting. Any audio recordings from interviews were securely stored, transcribed without identifying information, and were permanently de-

leted after transcription. All remaining data is stored on a password-protected device and used solely for academic purposes within this research project.

The interviews were recorded for transcription purposes. All identifying information was removed immediately. The recordings were stored securely and were deleted once transcribed. The transcription process was concluded a week after the last interview. Therefore, all recordings were deleted a week after the last interview.

User testing and interviews took place on the University campus, and all participants were informed that they may withdraw at any time during testing and for up to two weeks thereafter.

All participants in the study were over 18 years of age and physically able to manipulate the prototype.

4 Process

4.1 Phase 1: Exploration and Contextualisation

4.1.1 Design Ideation

During the initial ideation phase, the primary objective was to move beyond the "glass case" limitation of traditional museum curation. By leveraging embodied cognition, the design aimed to improve information recall through physical engagement. This stage involved the exploration of haptic-driven concepts to determine which interaction model would improve information recall and increase visitor engagement the most.

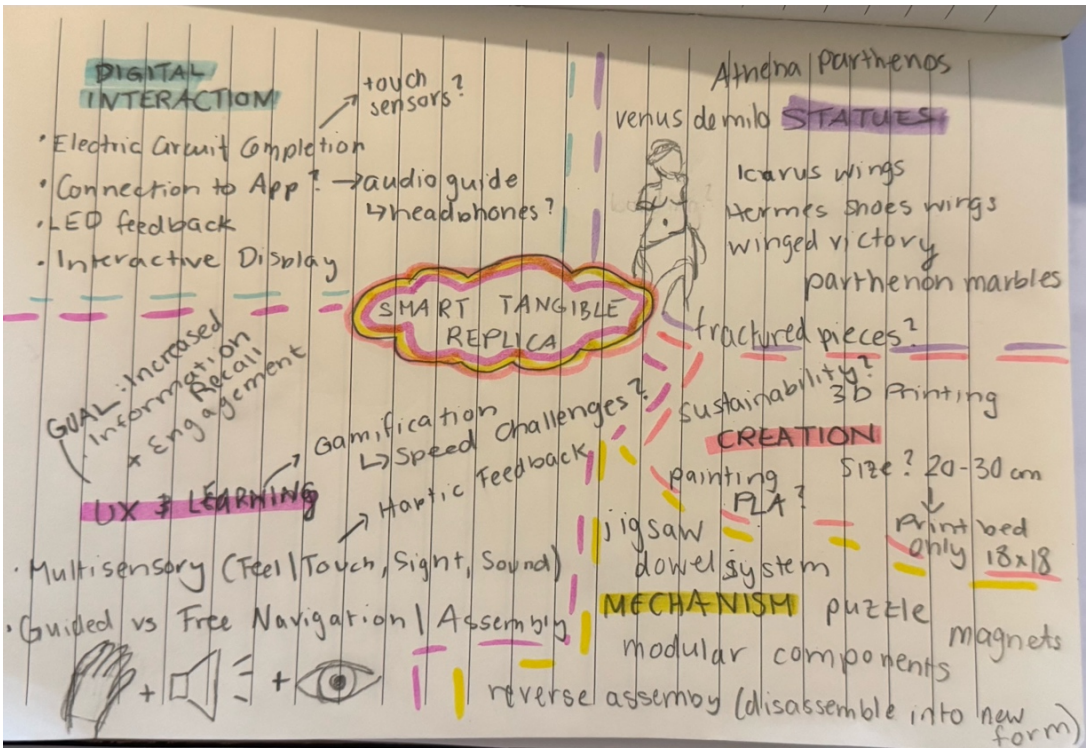


Figure 10: Brainstorming Mind Map

Initially, the project explored the concept of a Fractured Narrative, which centred on a 1:1 scale replica of a hand from an ancient Greek statue (see Figure 11). In this iteration, the hand served as a haptic interface, with capacitive touch sensors embedded beneath the surface. When a visitor touched specific areas, such as the palm or a broken finger, it would trigger a localised audio track detailing the history of that specific fracture or the craftsman's technique. While this concept excelled in tactile intimacy, it was ultimately deemed too passive. The interaction was a "point-and-click" mechanism rendered in physical form. It lacked the cognitive challenge needed to anchor information in the visitor's long-term memory.

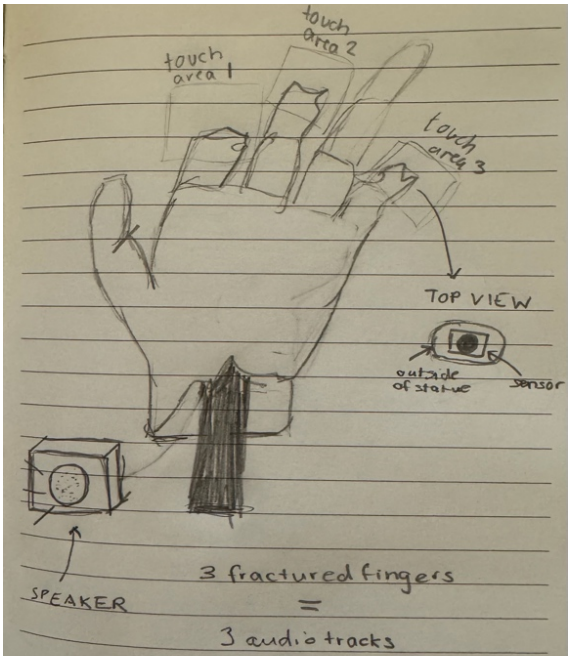


Figure 11: Fractured Narrative Sketch (Idea 1)

A second iteration investigated the use of a wing, a large-scale sculptural segment designed to interact with a spatial projection (see Figure 12). The design was inspired by the Greek Myth of Icarus. In this design, the visitor would adjust the wing's orientation to unlock different historical layers projected onto the gallery wall. Through low-fidelity sketching, it became apparent that this approach placed too much emphasis on the replica and digital projection, potentially detracting from the original artefact itself. Additionally, there was a risk that the visitor would focus on the wall rather than the original, thereby undermining the primary goal of museums, to display historical artefacts.

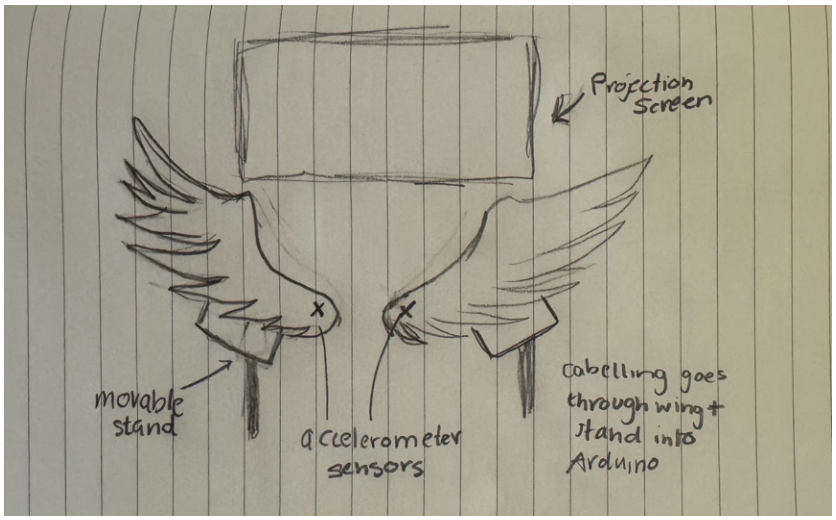


Figure 12: Wing Projection Sketch (Idea 2)

The transition to the puzzle assembly model represented a synthesis of the strengths of previous iterations whilst addressing their weaknesses. By requiring the visitor to physically reconstruct the replica piece, the exhibit moved from passive touching to active construction.

This iteration was selected because it satisfied the embodied cognition theory. By physically building the object, the visitor mentally builds the narrative.

Figure 13: Mood Board Puzzle Mechanisms

Figure 14: Mood Board Ancient Greek Statue

Following the selection of the puzzle concept, the design process moved into structural refinement. This began with a series of brainstorming sessions and mood-boarding to establish the aesthetic requirements and possible puzzle mechanisms of the replica. Early sketches were used to map possible physical movement, ensuring that the kinaesthetic action was the primary driver of the educational experience.

Following this ideation phase, the conceptual direction of the system was consolidated into a defined design (see Figure 15). Drawing from the final sketches, the experience was envisioned as follows: a visitor approaches the exhibit to find the fragmented pieces of a Greek statue laid out in a disassembled state. They are invited to reconstruct it, and upon successful assembly, an audiovisual response is triggered as a reward for their engagement.

At this stage, the precise mechanism by which the system would detect and validate a completed assembly remained an open question (see Figure 16). This question was subsequently addressed in the literature review, which drew on Marshall et al. (2016) and informed the

decision to adopt NFC technology as the detection mechanism. The subsequent sections work towards establishing the functional requirements and system flow that would bring this experience to life.

Figure 15: Initial Sketch of the Prototype

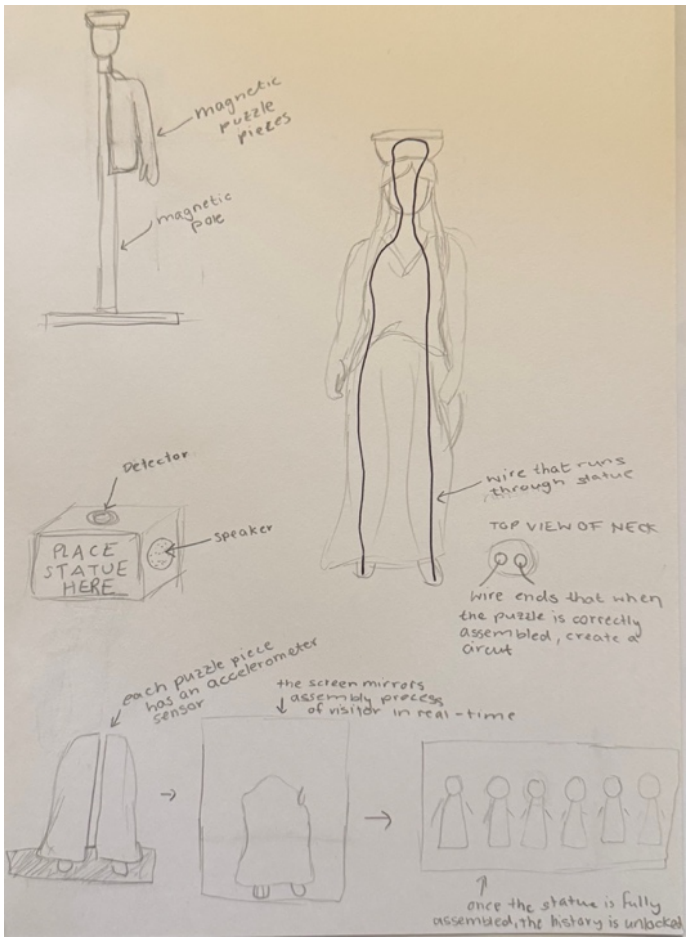


Figure 16: Sketches of possible mechanisms

4.1.2 Functional Specifications

The core of this phase was to define the TSR's design requirements as a sequential puzzle to ensure high visitor engagement and maximise information recall. The following design was decided upon.

The final model needed to be segmented into six pieces to create a multi-step assembly challenge. The puzzle was designed for a specific difficulty level: complex enough to engage visitors but simple enough to maintain a high success rate and a low reset time for museum staff. Previous versions had twelve and eleven pieces. However, due to the resulting top heaviness of the replica and the small size of some of the pieces, it was decided to reduce the height of the replica and the number of pieces to six. This created a more stable puzzle. The design required precise placement of magnets to secure the assembly while simultaneously providing the correct spatial feedback. The assembled replica is placed on a designated base containing NFC readers, which determines the triggered output.

The visitor experience consists of a multimodal feedback system. The visual output consists of an animation of the original Caryatids of Erechtheion, as they are present in the Acropolis Museum in Athens. Depending on where the replica is placed, the corresponding Caryatid in the animation will be illuminated, thereby establishing a direct connection between the replica and the original artefact.

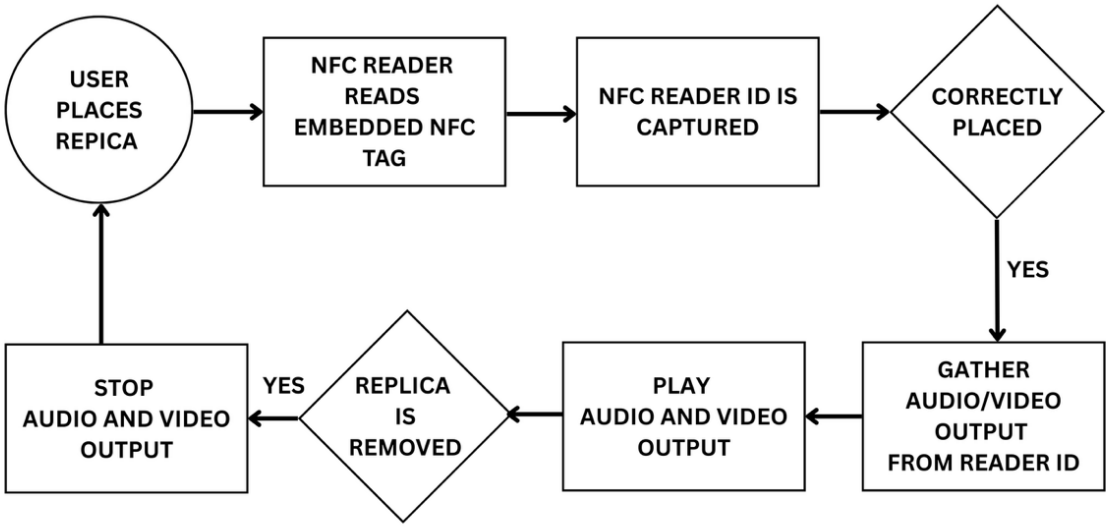


Figure 17: System Flow Diagram

The audio narrative tells the history and function of the Caryatids. The narration is divided into six parts, corresponding to the six Caryatids. The narration can be played in any order, allowing visitors to create their own narrative paths and listen at their preferred speed. The audio is accompanied by an informational text placed next to the replica. This is done to accommodate as many learning types as possible in this project.

The technical choices were driven by the need for sustainability and practicality, favouring low-cost, open-source, and maintainable components.

The project required a microcontroller to process the input and trigger the output. The Arduino Uno was selected as the central processing unit due to its low cost, ease of programming, and proven robustness for low-level input/output and direct sensor interaction. The project additionally required six NFC sensors. The Elechouse PN532 (V3) modules were selected for their high degree of versatility and are an industry-standard module with extensive documentation and mature library support, such as the Adafruit PN532 library used for this project, which aligns with the project's requirements for long-term maintainability and reliable performance in a public exhibit setting. The library can be accessed from the Appendix (see Chapter 8.1).

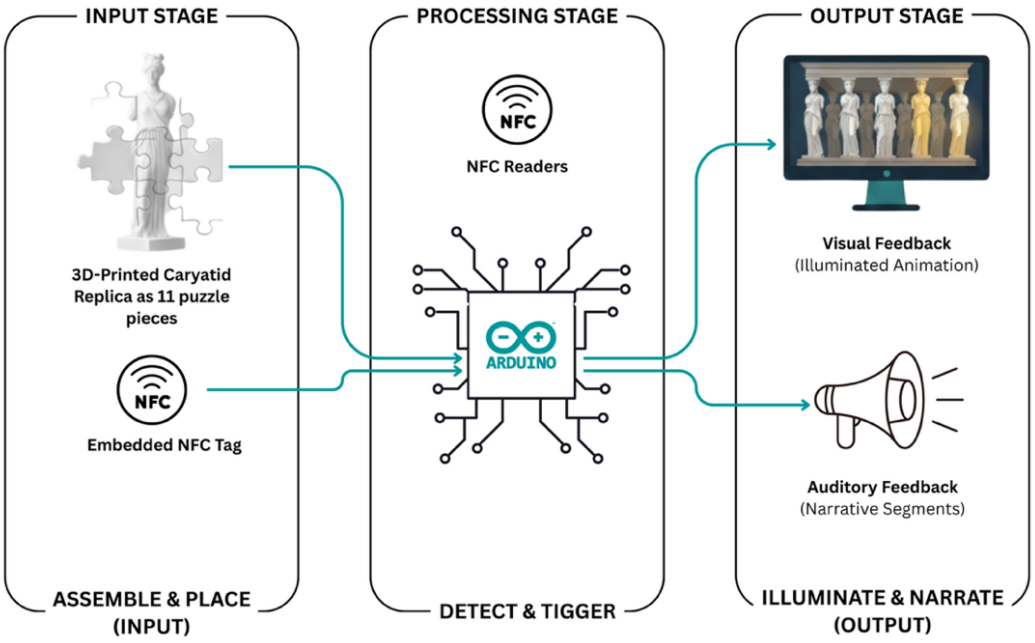


Figure 18: Technical Architecture of the System (AI-enhanced Sketch)

PLA Marble filament was chosen for its cost-effectiveness, ease of 3D printing, and its natural texture, which enhances the aesthetic of the replica while remaining durable for repeated

handling. Additionally, SUNLU PLA+ in black and white were used for the static testing environment, signage and electronic support. This filament was chosen due to its availability, high quality and low cost.

For the model modifications, Meshmixer and Blender were selected because they provide the capabilities required to create the final replica and any of the supporting pieces, such as the signage. The Bambu A1 mini and BambuStudio were selected as the 3D printer and slicer, respectively, because they were available during this research project.

Finally, it was decided to utilise laser cutting for the base design and enclosure of the electronics as it was the most time and cost-effective method.

4.2 Phase 2: Prototyping and Fabrication

This phase focuses on the physical and digital realisation of the prototype.

4.2.1 3D Printed Replica

The first step was finding a suitable model of the Caryatid that could later be modified and printed. When selecting a model, several aspects were prioritised. Firstly, it needed to be a high-quality, detailed model to fulfil the previously established design requirements. Furthermore, the model required specific Creative Commons licenses to permit modification and reproduction for this project.

The model chosen for this project is the "Copy of Caryatid C, Erechtheion of the Acropolis" from SMK - Statens Museum for Kunst, which was uploaded to the MyMiniFactory website. This model met both criteria and was deemed ideal for this project.

The model was initially printed at a scale of 0.05, resulting in a height of approximately 12 cm. This first print was completed to ensure that the mesh was undamaged and that the detail of the digital model would transfer to the physical print. It was printed at a reduced size to reduce printing time and material costs.

Figure 19: First Prints of the Caryatid Model in Black and Marble-like PLA

Once it was established that the model could be successfully printed, it was printed in the Marble-like PLA to check the material's realism. Next, the work on modifying it began. The original STL file had a wall thickness of roughly 1 mm. This project required a wall thickness of 8 mm to accommodate the magnets that would serve as closing mechanisms. To achieve this, the wall thickness would need to be increased prior to segmenting the model and inserting magnet indents.

In Meshmixer, the model was scaled by 0.12 to a height of 27.8 cm. This height was determined through subjective evaluation to optimise the assembly process. This was later reduced to 23 cm due to the previous version's top-heaviness mentioned in Chapter 4.1. The height of 23 cm proved to be a sweet spot that maintained the statue's aesthetic majesty while ensuring a low centre of gravity.

Figure 20: Tangible Smart Replica 27.8 cm version (assembled)

Furthermore, the segmentation was later reduced from an overly complex eleven-piece set to a more intuitive six-piece assembly. This additionally resulted in more durable pieces.

Figure 21: 11-piece version

Figure 22: 6-piece version

Once the model was scaled down, the "Hollow" tool was applied. After multiple iterations, an offset of 8.8 mm for the headpiece and 8 mm for the rest of the Caryatid was identified as the optimal balance among magnet placement, print time, and aesthetic design. The Mesh Density was increased from 128 to 250 to ensure a smooth interior wall, which was important

because segmentation into puzzle pieces would reveal the model's interior. Once all modifications were completed, the model was exported as an OBJ file.

The OBJ was then imported into Blender, where the model was rotated and positioned at the origin, after which a plane was created. The plane was scaled up until it could pass through the model. A solidify modifier was applied to the plane before transforming it to where the first segmentation would take place. Once the plane was positioned correctly, the model modifier was selected, and the difference Boolean operations were applied. Then, the Edit mode was opened and "Separate By Loose Parts" was chosen. This separated the two model pieces that had just been segmented by the plane. The areas to segment were selected based on the following criteria: minimal interference with the model's accuracy, structural integrity, and appropriate puzzle piece size. The segmentation process was repeated until the model was split into twelve pieces. This was later adjusted to eleven fragments and then to six fragments due to the small size of some pieces and the previously mentioned usability issues.

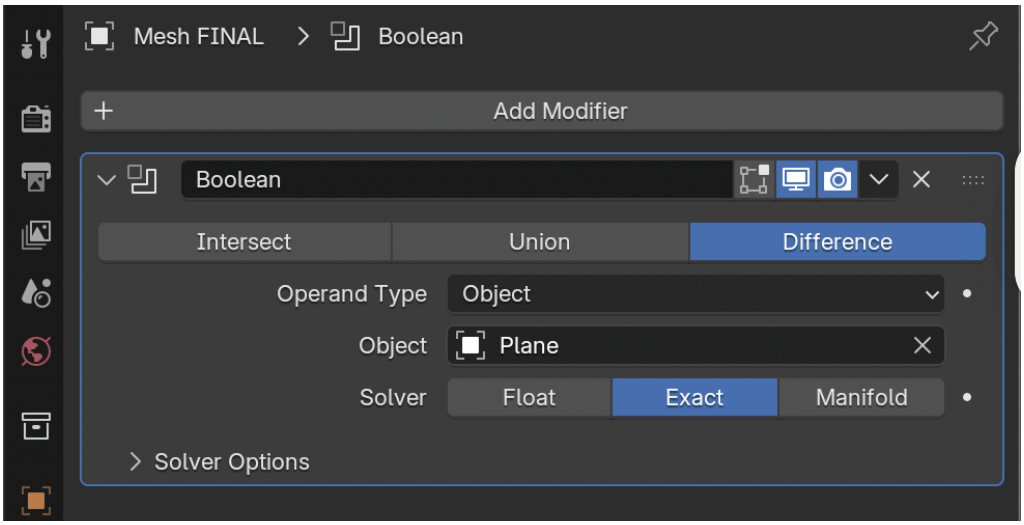


Figure 23: Boolean Operation in Blender

Next, a cylinder was created as a substitute for a magnet. The magnets chosen for this project were 4×2mm strong mini magnets, which had been used effectively as a closing mechanism in a previous 3D-printing project. They are a low-cost option available in bulk and align with the design criteria outlined in the literature review. The cylinder was assigned a 0.2 mm tolerance and positioned at the model's previously established offset distance, using a Boolean difference operation. This created a magnet-sized indentation in the offset. The final version uses a total of 64 magnets.

After trialling multiple methods for including the NFC tag in the model base, it was decided to use a 40 x 35 x 6 mm tag that came with the NFC reader. This tag was larger than a sticker-type NFC tag but offered greater reliability, which was prioritised for this project. To integrate the tag into the base of the model, the integrated base plate included in the original model from SMK - Statens Museum for Kunst (see Figure 25) was removed using a Boolean operation. This provided a flat surface the size of the statue's feet. This surface was then extruded to 0.61cm to fully enclose the tag. An enclosure for the tag was modelled and subtracted from the new base surface to create an opening that could fit the tag. During slicing, a pause was added to the printing process, during which the tag was integrated into the model.

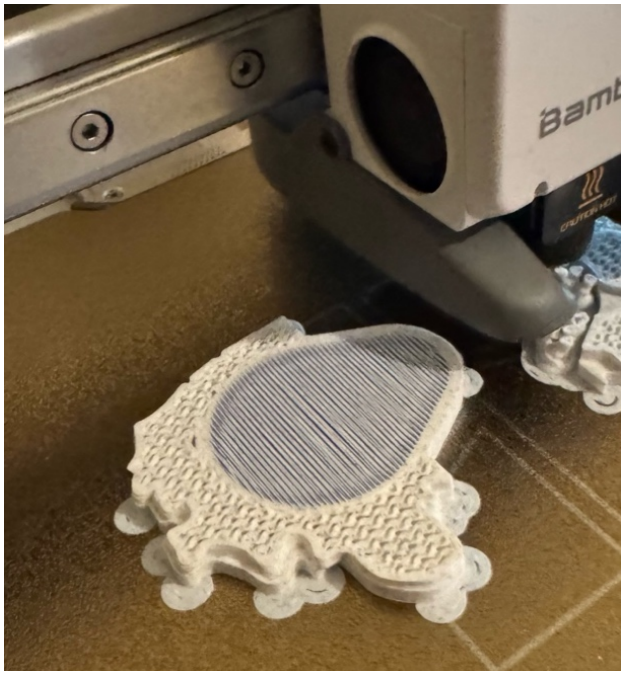


Figure 24: 3D Print while it is embedding a Blue NFC Tag

Figure 25: The Original Base Plate

Once the model was fully modified, all components were exported as one STL file. The file was imported into BambuStudio, an open-source slicer. There, the individual puzzle pieces were separated and automatically arranged by the slicer for optimal printing. For the first print (27 cm-12-piece statue), default printing settings were used: 0.2 mm layer height an infill of 15%. This was later changed to increase the print quality. Supports were added to the hands and the overhang of the drapery. This print took 10 hours and 46 minutes and used approximately 230 grams of filament. The filament selected for this project is Marble PLA, which has a natu-

ral-stone-like texture. This filament was chosen because it is cost-effective and gives the visitor a more realistic appearance than other coloured PLA options. The decision to use PLA rather than materials such as resin and ABS was justified and supported by the literature review.

Filament	Model	Support	Total
■ 1	75.93 m 222.82 g	2.97 m 8.73 g	78.91 m 231.55 g
Total cost: 6.94			
Time Estimation			
Plate 1		4h41m	
Plate 2		1h57m	
Plate 3		4h8m	
Total		10h46m	

Figure 26: Slicing Details of Print One

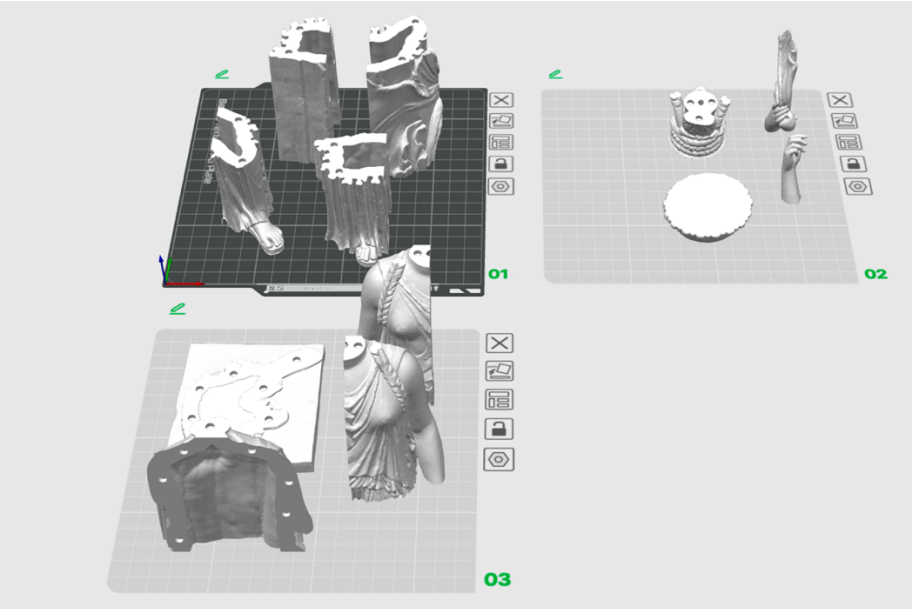


Figure 27: Print Layout in BambuStudio for Print One

After the first full print concluded, a few problems were evident immediately and were fixed during the development of the final version. The model's base plate lifted during printing and deformed. This was easily fixed by adding a brim around the edge of the base piece during the next print. Additionally, some of the magnet indents were too small to fully accommodate the magnet, so an additional millimetre of tolerance was applied. Furthermore, the right-hand puzzle piece was too small and, due to a single magnet connection, could not connect securely. Because of concerns that the piece might be lost quickly, the hand was reattached to the arm and printed as a single unit, reducing the 12-piece puzzle to 11-pieces.

The modified model was reimported into BambuStudio for printing. This time, a layer height of 0.12 mm was selected to increase model detail and improve the replica's realism. More supports were added to the model due to increased printing time and concerns that overhangs would collapse. Additionally, some filament settings were adjusted to improve print quality, increase weight and durability, and enhance the smoothness of the outer layer. The adjusted settings included increasing the flow ratio to 1.01, reducing the nozzle print temperature to 210 ° for all layers except the initial one, reducing the cooling overhang threshold to 25%, and increasing the fan speed to 100%. Furthermore, the initial layer height was increased to 0.23 mm, the ironing setting was turned on for the top surfaces, the ironing pattern was set to rectilinear, the speed was set to 60 mm/s, and the flow was set to 21%. The sparse infill density was increased from 15% to 40%, and the pattern was set to Gyroid. Lastly, the top Z distance was set to 0.31 mm. These parameters were determined through trial and error and proved to offer the best printing experience, quality, and durability of the print. The print was again printed with a statue size of 27 cm. However, after the statue pieces finished printing, the previously mentioned top heaviness became apparent. The model was resized to 23 cm, and the number of pieces was reduced to six. Additionally, after combining the crown and head of the model into one piece, the print showed drooping around the nose. Previously, the head was printed upside down to avoid this. However, as the crown offers an uneven surface, this was no longer possible. The decision was made to even out the top surface of the crown, so the crown-and-head combined piece could be printed upside down again, reducing the drooping around the nose.

Lastly, a fuzzy skin/stone-like printing texture was trialled. For this, the point distance was set to 0.3, and the point thickness was set to 0.175. However, this texture did not work on detailed pieces and made them look like a poor-quality print rather than a purposely chosen print texture.

Figure 28: Upper Body piece printed in the fuzzy skin texture (left) and normal texture (right)

Figure 29: Head piece printed in the fuzzy skin texture (left) and normal texture (right)

The total printing time for the updated 23-cm-6-piece puzzle was 17 hours and 21 minutes, and approximately 200 grams of filament were used.

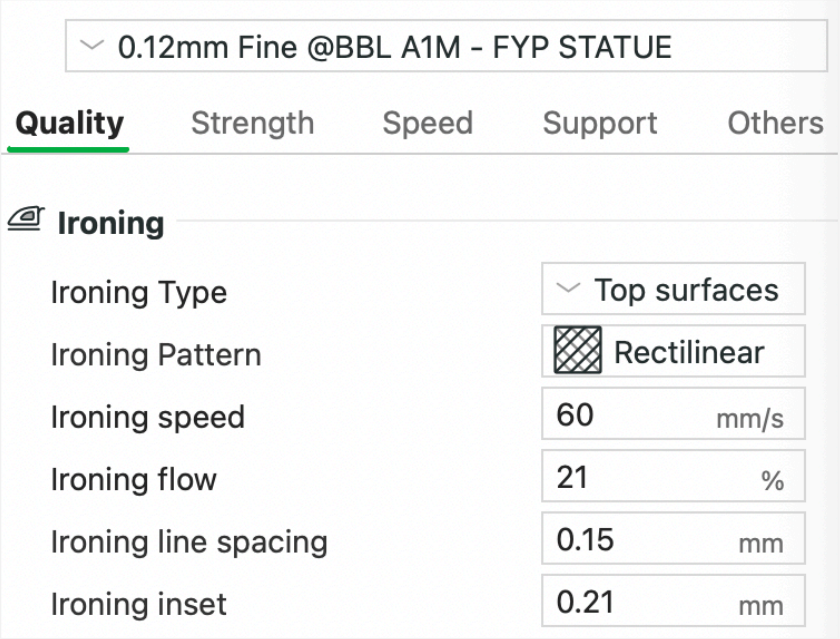


Figure 30: Ironing Settings in BambuStudio (Final Print)

Filament	Model	Support	Total
■ 1	66.09 m 193.92 g	2.05 m 6.01 g	68.14 m 199.94 g
Total cost: 6.00			
Time Estimation			
Plate 1		5h59m	
Plate 2		5h21m	
Plate 3		6h1m	
Total		17h21m	

Figure 31: Slicing Details of Final Print

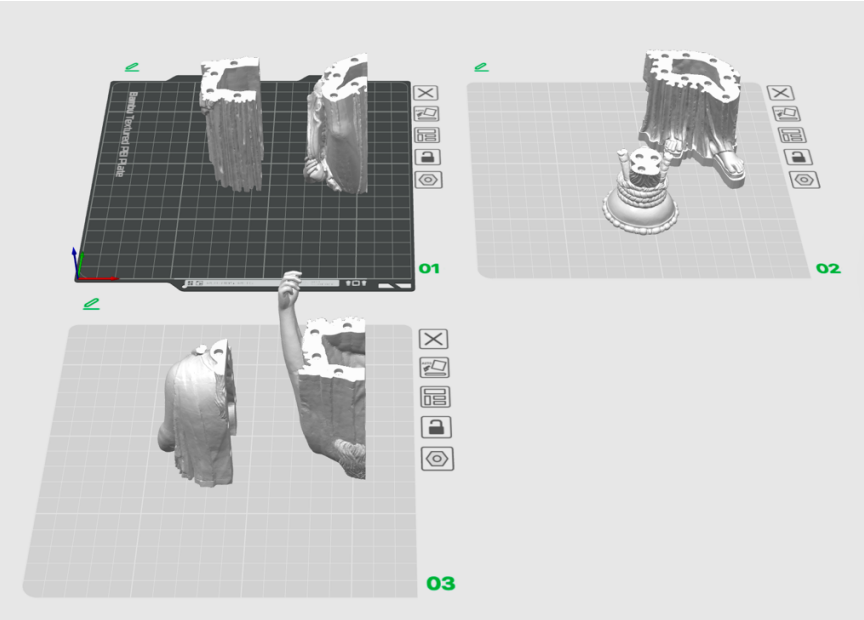


Figure 32: Print Layout in BambuStudio (Final Print)

Once the model was printed, the supports were removed using a deburring tool, sandpaper and a wire cutter. The magnets were integrated using super glue. Before glueing each magnet, the orientation had to be verified to ensure the magnets would not repel. Once all the magnets were glued in, the model created was a successful 3D puzzle of one of the Caryatids of Erechtheion.

Figure 34: Final Version of Statue with Visible Magnets

Figure 33: Final Version of Statue

4.2.2 Static Testing Environment Design

Additionally, to the Tangible Smart Replica, a static exhibition environmental model was produced. The secondary model consists of the temple base and five of the original six Caryatid statues. For the five static Caryatids, the "Copy of Caryatid C, Erechtheion of the Acropolis"

model from SMK was again selected. This specific model was chosen as it represents the highest-quality freely available scan of the Caryatids. While the original temple features six unique statues, this single model was duplicated for the five positions to ensure high print quality. Each statue was scaled to a height of 163 mm, a dimension determined by balancing aesthetic appeal with fabrication efficiency. It was decided to only display five out of the six original statues to replicate the artefact as it is displayed in the Acropolis Museum.

The temple base was modelled in Blender as a series of six modular cubes. These were designed with dimensions of 100 x 100 x 35 mm and 70 x 100 x 35 mm to accommodate the scaled footprints of the statues while remaining within the printer's build volume.

Figure 35: Static Testing Environment

The print parameters were optimised for speed rather than tactile durability, as this model was not handled by participants. The layer height was set to 0.2 mm with a 15% grid infill. This reduced the print time by over 50% compared to the settings used for the interactive puzzle pieces, where a higher density and finer resolution were required for weight and surface finish.

For this print, the SUNLU White PLA+ was chosen for two primary reasons. It is significantly more economical than the specialised Marble-like PLA used for the interactive replica. And as

the static environment is viewed from a distance, the subtle texture of marble PLA was deemed unnecessary. The white PLA provided sufficient visual clarity for the user testing experience without compromising the prototype's appearance. The total printing process took 26 hours and 47 minutes and used 784 grams of filament.

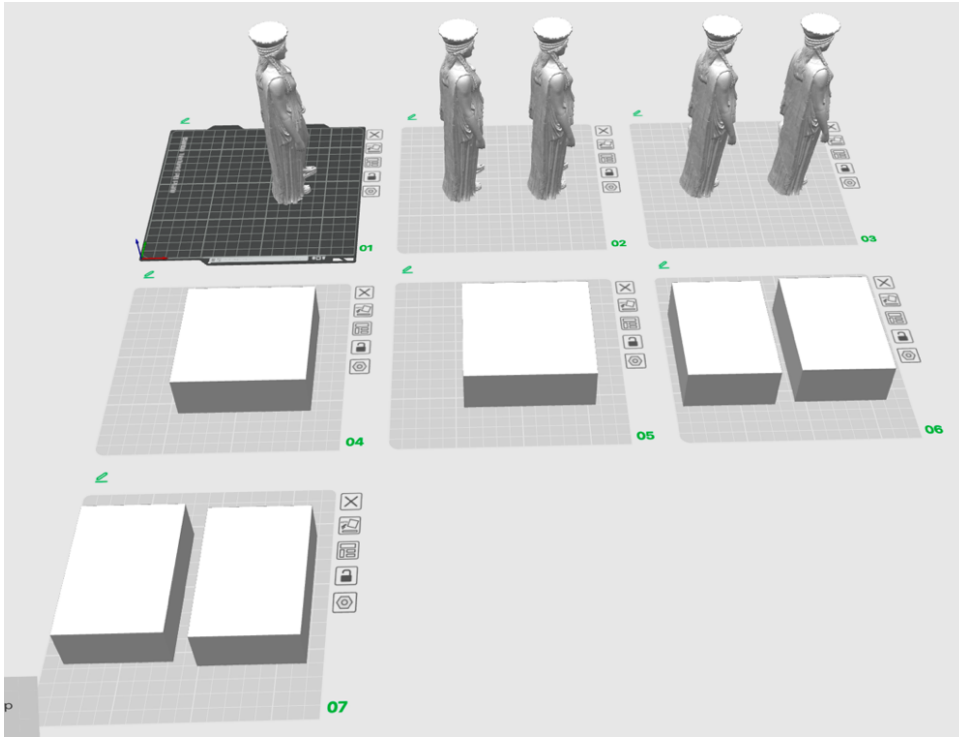


Figure 36: Print Layout in BambuStudio (Static Testing Environment Print)

Filament	Model	Support	Total
■ 1	248.05 m 751.77 g	10.61 m 32.16 g	258.67 m 783.93 g
Total cost: 19.59			
Time Estimation			
Plate 1		3h38m	
Plate 2		6h47m	
Plate 3		6h47m	
Plate 4		2h0m	
Plate 5		2h0m	
Plate 6		2h47m	
Plate 7		2h47m	
Total		1d2h47m	

Figure 37: Slicing Details of Static Testing Environment Print

4.2.3 Laser Cut Base

As established previously, the scale of the electronics enclosure necessitated laser cutting as the primary fabrication method rather than 3D printing due to its size. The design process

began by mapping the footprint of the statue's feet to determine the precise diameters of the NFC reader slots. Early sketches of the architecture also addressed the placement of NFC readers and the size of the circular indents on the base's lid for the statue's feet. This needed to be significantly larger than originally expected due to the statue's asymmetrical feet and the minimal distance required between the readers for them to function properly. The circular geometry was duplicated and arrayed five times to create the interaction points. This was later used as a blueprint for the Vector drawing that determined the size of the laser-cut pieces.

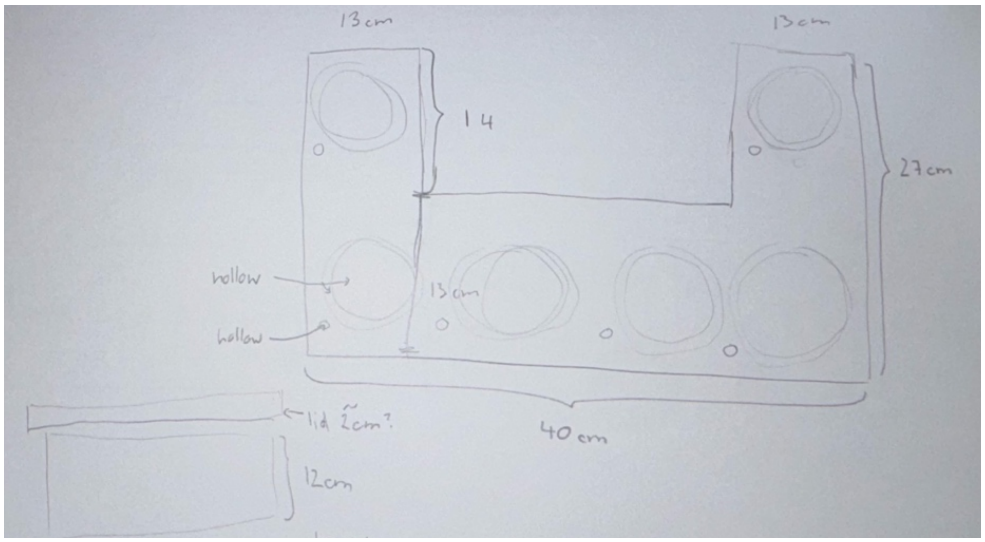


Figure 38: Early Sketch of Laser-Cut Base

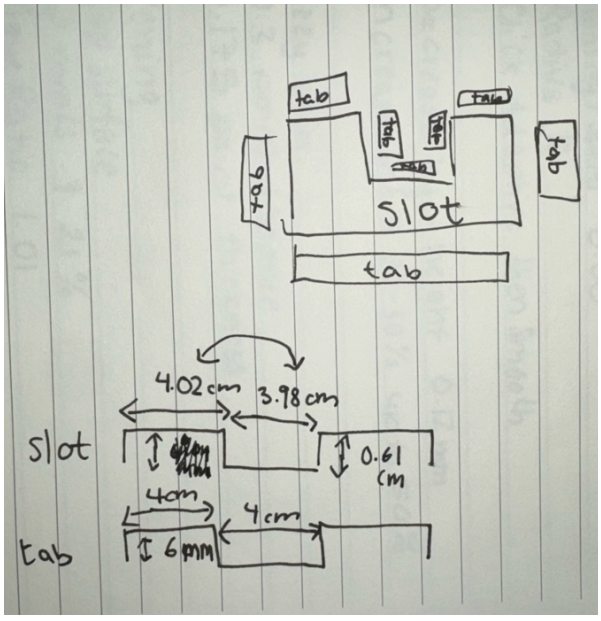


Figure 39: Early Sketch of tab and slot system

To accommodate the internal hardware, which includes five NFC readers, the LEDs, and the Arduino microcontroller, a base dimension of 600 x 300 mm was set. A height of 100 mm was selected to provide sufficient internal volume for organised cable management and structural stability. These measurements were determined after multiple iterations of sketches and pa-

per prototypes. Once the dimensions were verified, the layout was digitised as a vector file in Affinity Designer (now Vector) for compatibility with the laser cutter's software interface.

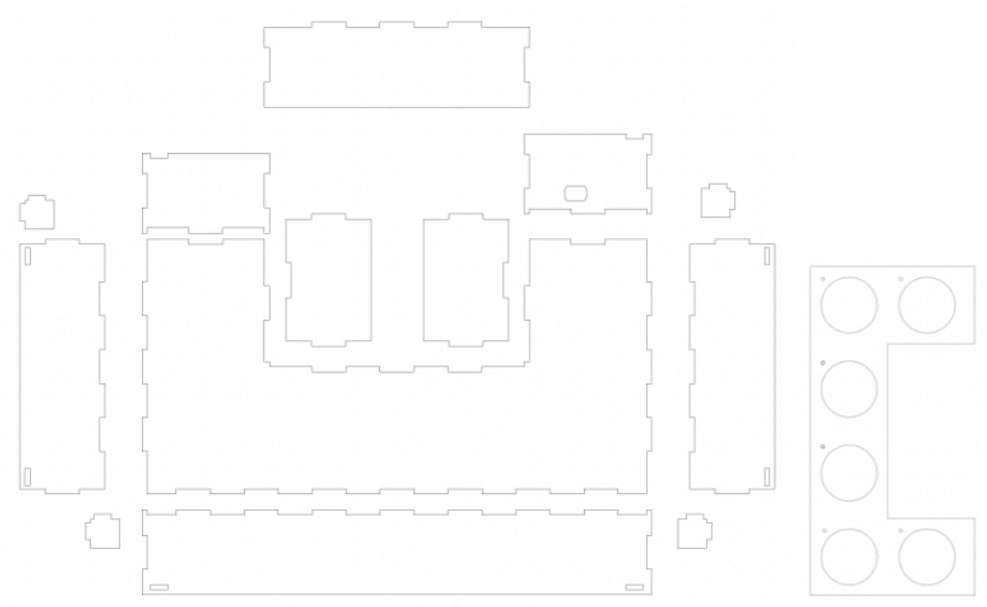


Figure 40: 2D vector drawing of the Base

Following the digitisation of the initial base components, finger joints were added to all of the pieces, except the lid. Each finger joint measures roughly 40x6mm. This size proved to be the optimal balance between aesthetic symmetry and structural rigidity. To achieve a high-precision friction fit, a kerf compensation of 0.2 mm was applied to the cutting paths.

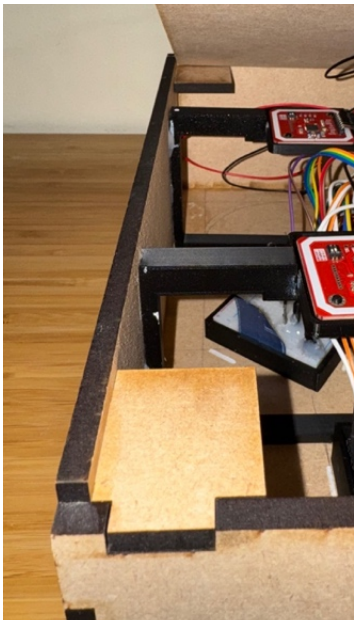


Figure 41: Internal Corner Support for the Lid

To facilitate a secure yet accessible enclosure, a recessed lid mechanism was designed using internal corner supports. Four 35x35 mm squares were cut and slotted into four of the internal

corners of the base walls, positioned 6mm below the upper edge. This offset corresponds to the thickness of the MDF, allowing the lid to sit within the perimeter of the walls and rest on the internal corner supports while remaining perfectly flush with the top of the enclosure. This design provides the necessary structural stability to support the replica's weight while ensuring straightforward, tool-free access to the internal circuitry and NFC hardware for maintenance.

The vector drawing was then uploaded to the Laser Cutter by selecting the Laser Cutter as a printer for the file. The Laser Cutter used for this project was an Epilog Laser Fusion M2 and used the EpilogApp for configuration. Within EpilogApp, the job type was set to “Vector”. In the Vector Settings, the Speed was set to 3%, the Power to 100%, and the Frequency to 10 Hz. These are the default settings for Wood MDF 6mm when using the Epilog Laser.

Figure 42: First Laser Cut Version of the Lid

After the first version of the base was cut, one issue became apparent immediately. The rear and adjacent wall panels revealed a 6 mm dimensional error, due to an oversight in accounting for material thickness during the joint-calculation phase. However, this was easily fixed. Before the final cut, the design was further iterated to include a dedicated cable port for the Arduino power supply. After determining the correct fit of all pieces, the lid was redesigned to include circular engravings for the statue placement and holes for the LED bulbs. For long-term museum durability, the panels were assembled using professional-grade wood adhesive to ensure the enclosure could withstand public interaction.

Figure 43: Finished Base

4.2.4 Physical Computing

The physical computing infrastructure serves as the bridge between the 3D-printed replica and the digital narrative. This section details the iterative development of the NFC sensing array, the hardware stabilisation of the LED indicators, and the serial communication protocol.

Software

The NFC tags were formatted and written to using the code library from Adafruit. This code library can be accessed through the link in the appendix.

Initially, the system was tested using a single NFC reader via the I2C (Inter-Integrated Circuit) protocol. While successful in isolation, scaling to six readers introduced significant challenges in addressing conflicts and data instability. Consequently, the architecture was transitioned to the SPI (Serial Peripheral Interface). SPI offered superior reliability for managing multiple peripheral devices, as each reader could be explicitly addressed via a dedicated Cable Select (CS) pin, ensuring cleaner data transmission across the expanded bus.

A primary challenge in the interaction design was the trade-off between latency, or rather responsiveness, and stability, including preventing false negatives. The software originally utilised a linear loop, checking if each of the six readers was present and taking around 100ms if it was not. This resulted in a total cycle time of 600ms.

To prevent false negatives, in which a reader momentarily fails to detect a present tag, a miss-threshold of three consecutive failed checks was implemented. While this stabilised the connection, it increased the removal detection latency to almost 2 seconds (600 ms × 3 = 1.8

seconds), which was deemed too slow for an instant user experience. A state-dependent polling logic was developed. When no tags are detected, the system polls all readers at 100 ms intervals. However, once a tag is identified, the system locks focus on that specific reader and polls it every 50 ms. Since the exhibit is designed to play only one video at a time, this optimisation reduced the removal detection time from 1.8 seconds to 150 ms. This is a 91% improvement in responsiveness. The miss threshold was then safely increased to five cycles, providing strong connection security without sacrificing perceived speed.

After some long-duration testing, it was observed that individual readers occasionally became unresponsive due to electromagnetic interference or bus errors. To ensure museum-grade reliability, a Health Check algorithm was implemented. Every five seconds, the system performs a non-intrusive scan of all inactive readers. If a reader fails to respond, the software attempts an automated soft restart of the specific reader. This background recovery is invisible to the user, ensuring the exhibit remains functional without requiring manual intervention from museum staff.

While the Arduino manages the physical sensing of the NFC tags, the visual output is handled by Processing, an open-source graphical library and integrated development environment. To bridge these two platforms, a serial communication protocol was established using the methodology outlined in the SparkFun tutorial "Connecting Arduino to Processing". The link to this tutorial is in the Appendix (see Chapter 8.1).

The system utilises the processing.serial library to listen for incoming data from the Arduino. A high baud rate of 115200 was selected to minimise latency between the replica's physical placement and the visual response. The software employs a specific string-based command protocol. Firstly, the START_[ID] command, which initiates the specific narrative for the specific statue placement. Secondly, the STOP_[ID] command, which triggers an end video if the replica is removed before the video naturally concludes.

The sketch is designed to manage three distinct visual states to ensure a seamless visitor experience, as prioritised in the design requirements. The first state is the idle state. When no interaction is detected, a high-resolution idle.png is displayed. The second state is the main narrative. Upon receiving a START command, the system retrieves the corresponding clip from the mainClips array. And lastly, the dynamic termination. If a user removes the statue mid-narrative, the processCommand() function triggers a transition to an end clip (endClips). This

provides a logical narrative conclusion rather than an abrupt cut, enhancing the perceived quality of the exhibit.

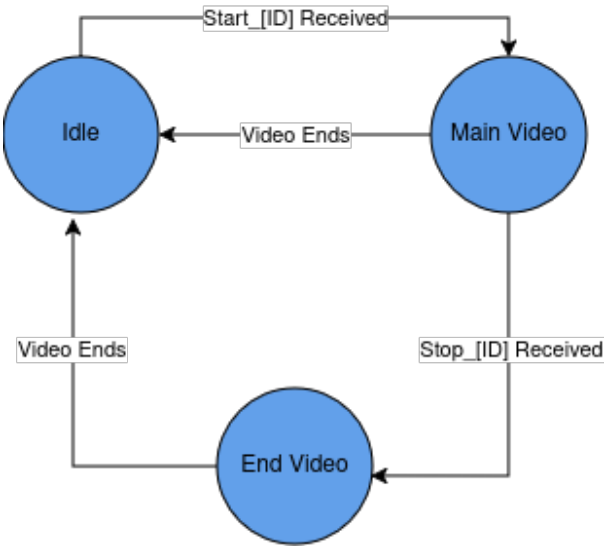


Figure 44: State Flow Diagram

To maintain visual consistency across different display aspect ratios, a custom drawCentered() function was implemented. This function calculates the aspect ratio of the active media and scales it to fit the screen dimensions using the formula:

$$targetHeight = \frac{targetWidth}{aspectRatio}$$

This ensures that whether the system is running on a standard monitor or a large-scale museum projector, the content remains centred and undistorted.

Furthermore, the isTransitioning boolean and checkVideoEnd() logic prevent frame-clashing or overlapping audio. By checking if a movie is within 0.2 seconds of its duration, the system can cleanly stop the current process and return to the idle state, ensuring the exhibit is always ready for the next visitor without manual intervention.

Hardware

The project utilises an Arduino Uno WiFi Rev2 as the central microcontroller and six Elechouse PN532 (V3) modules for NFC sensing. To facilitate the high-speed data transfer required for six independent NFC readers, the Serial Peripheral Interface (SPI) protocol was employed as mentioned.

SPI is a synchronous serial communication interface used for short-distance communication, typically in embedded systems. It follows a "Master-Slave" architecture in which the Arduino (Master) controls data flow to the NFC readers (Slaves).

In this project, the six SPI lines were utilised. The SCK (Serial Clock) line carries the clock signal generated by the Arduino to synchronise data transmission between the devices. The MOSI (Master Out Slave In) line is the primary data line used by the Arduino to send instructions or configurations to the NFC readers. The MISO (Master In Slave Out) line is the data line through which the NFC readers send tag-detection information back to the Arduino. The SS / CS (Slave Select / Chip Select) line is a dedicated digital line for each reader. When the Arduino pulls a specific SS line "low," it activates that individual reader to send or receive data, preventing interference from the other five sensors on the same bus.

On the Arduino Uno WiFi Rev2, the SPI bus is most reliably accessed via the ICSP (In-Circuit Serial Programming) header. Using the ICSP pins allowed for a centralised connection point for the shared SCK, MISO, and MOSI lines across all six readers.

The NFC readers were arranged spatially in a counterclockwise layout, beginning at "Position 1" and concluding at "Position 6." To manage the complexity of the shared bus, a breadboard was used with a strict colour-coding standard implemented for maintenance and trouble-shooting.

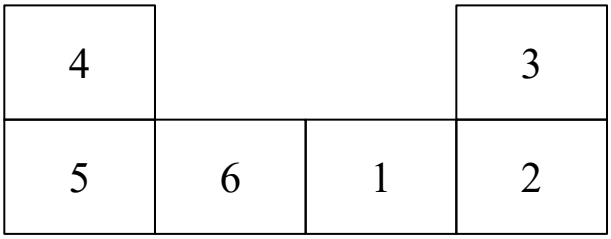


Figure 45: NFC Reader Placement

TABLE 6: NFC AND LED PIN ALLOCATION MAPPING

Component	**Position**	**SS / Signal Pin**	**Cable Colour**
NFC Reader 1	1	D5	Orange
NFC Reader 2	2	D6	Orange
NFC Reader 3	3	D7	Orange

NFC Reader 4	4	D2	Orange
NFC Reader 5	5	D3	Orange
NFC Reader 6	6	D4	Orange
Shared Bus	VCC	5V	Red
Shared Bus	GND	GND	Brown
Shared Bus	MOSI	ICSP Pin 4 - MOSI	Yellow
Shared Bus	MISO	ICSP Pin 1 - MISO	Green
Shared Bus	SCK	ICSP Pin 3 - SCK	Blue

This setup of NFC readers was tested before incorporating the LEDs and extending the cabling to reach around the base.

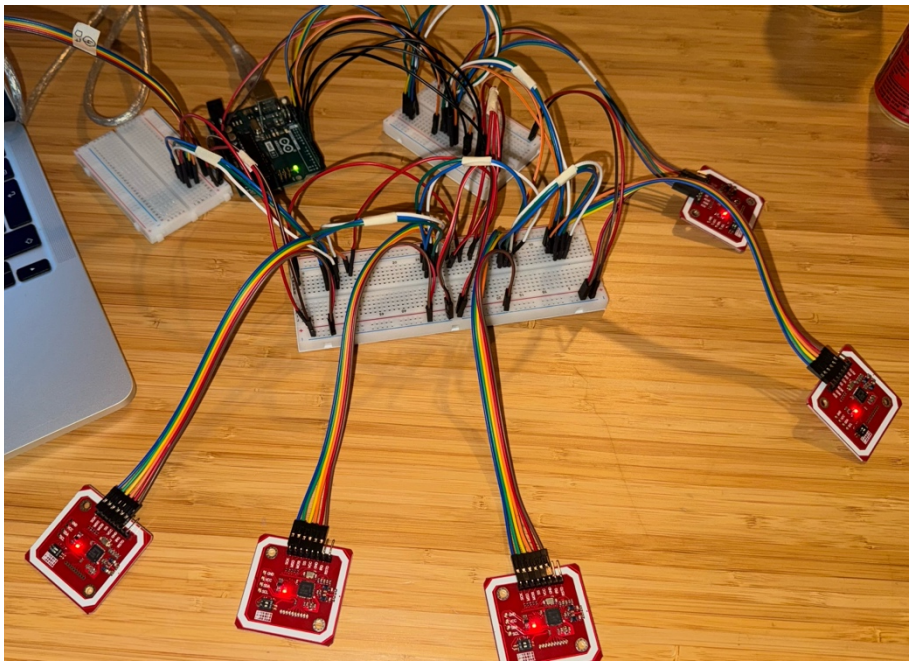


Figure 46: Initial NFC Set-up

To provide immediate visual feedback upon tag detection, six LEDs were integrated into the enclosure. These were mapped to the Arduino's Analogue pins (A0–A5), which were configured in the software to function as digital outputs. This preserved the primary digital pins for the NFC Slave Select lines. LED 1 was allocated A0, 2 was allocated A1, 3 connected to A2, 4 to A3, 5 to A4, and 6 to A5.

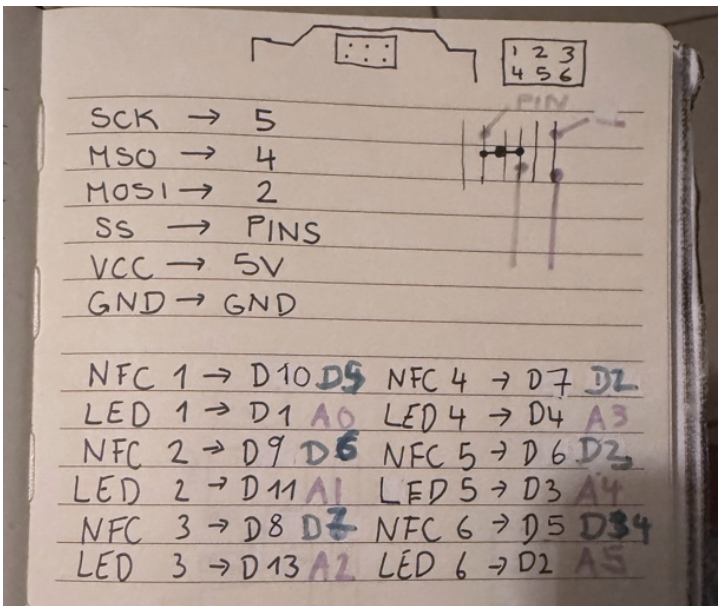


Figure 47: NFC Reader and LED Pin Allocation

The initial hardware prototype utilised individual 5 mm LEDs and 220 Ω resistors wired directly into a breadboard. However, the mechanical stress of transporting the exhibit caused frequent disconnections. To address these reliability issues, the prototype was upgraded with pre-wired, 3-5V-integrated LEDs, powered via the Arduino's 5V rail, housed in secure, screw-mounted casings. This transition improved the prototype in two key areas. Firstly, the secure housing prevented wires from loosening during public interaction. Secondly, the high-intensity LEDs provided superior visibility, ensuring that the feedback was distinguishable even under the high ambient lighting typical of a museum gallery.

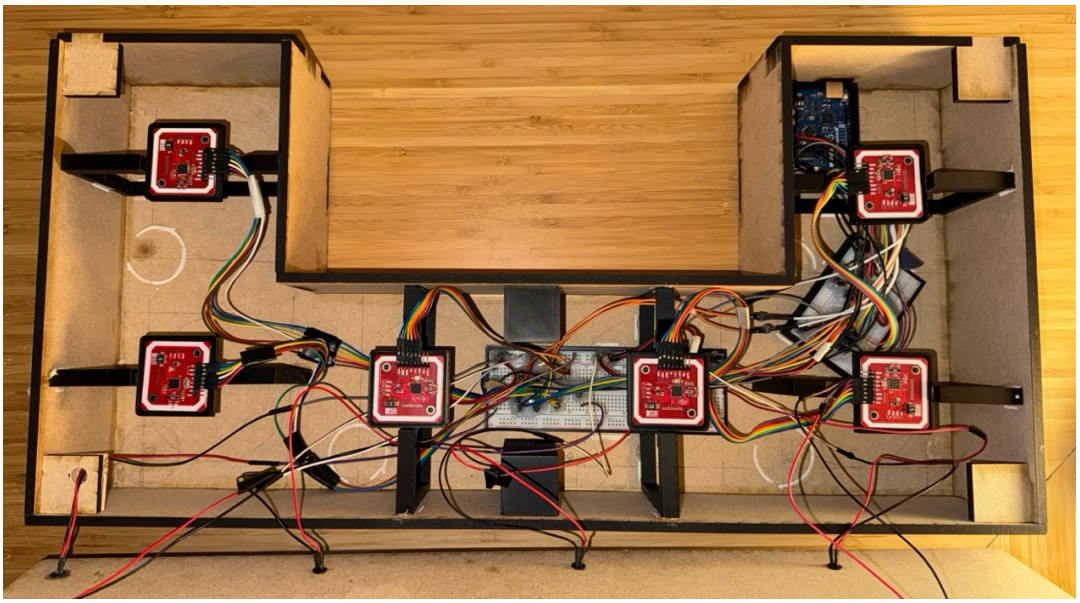


Figure 48: Electrical Components

To ensure long-term structural integrity and that the electronics remain secure during transport, most cables were fixed in place with hot glue or heat-shrinking tubing. The LED wires were the only exception, as the LED housings were specifically chosen with a diameter exceeding that of the lid's mounting apertures, thereby preventing the bulbs from slipping through the base. The LED wires must be threaded through the lid before they are connected to secure them in place. Leaving these wires unglued allows the lid to be easily removed if the exhibit needs maintenance or repairs.

4.2.5 Signage

To enhance the exhibit's usability and provide historical context in another format, five signs were 3D-printed. These signs serve as the primary interface for visitor guidance, establishing the exhibit's identity and encouraging tactile interaction.

The signage was modelled in Blender. The primary title sign was created on a 162 × 162 × 2 mm plane. To ensure maximum legibility, the Blender Text feature was utilised. The extrude setting was set to 0.6 mm, the bevel depth was set to 0.02 mm, and the line spacing was set to 1.1 mm.

To achieve a high-contrast finish without requiring post-print modifications, a manual multi-colour technique was employed. The signs were printed at a 0.12 mm with the Ironing feature enabled on the top surfaces to achieve a smooth finish. A "Pause" command was inserted into the G-code after the sixth layer, allowing a manual filament swap from SUNLU Black PLA+ (base) to White PLA+ (text). This dual-tone approach ensured that the raised lettering was immediately visible against the dark background, fulfilling the accessibility requirements for high-contrast museum displays.

Figure 49: 3D Printed Sign of Exhibit Title

The primary historical information was split across two separate panels. This partitioning served two purposes. Firstly, it allowed the panels to fit within the physical dimensions of the printing bed, and secondly, splitting the content prevented cognitive overload, a common issue in museum design, where visitors are deterred by dense walls of text. By breaking the information into digestible segments, engagement and retention rates are likely to improve.

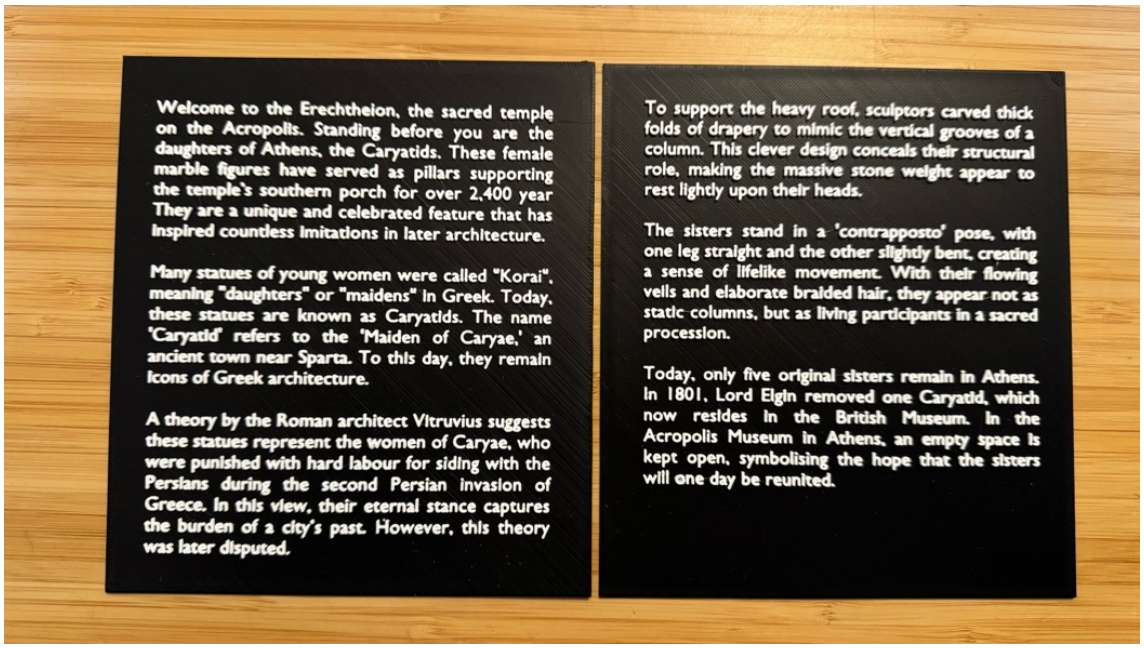


Figure 50: 3D-Printed Information Signs

Three additional signs were produced for the testing environment and user guidance. A smaller version of the exhibition title sign, 122 x 34 x 1.6 mm, was printed for the static testing environment. A “Please touch!” sign, 73 x 160 x 1.76 mm, was designed, printed and then placed prominently on the box housing the replica pieces. This sign used a 0.2 mm layer height to optimise production speed, as the larger font size remained highly legible at this resolution. Brims were added to the print configuration to prevent warping or corner lifting, ensuring a perfectly flat mounting surface. Lastly, individual 20 mm letters were generated in Bambu Studio to spell "START HERE" around the circular engraving on the base lid. These were secured with super glue to provide a clear starting point for the interaction sequence.

The total fabrication time for the signage was 5 hours and 52 minutes, utilising 84.07 grams of filament.

Figure 51: 3D Printed Lettering on the Base

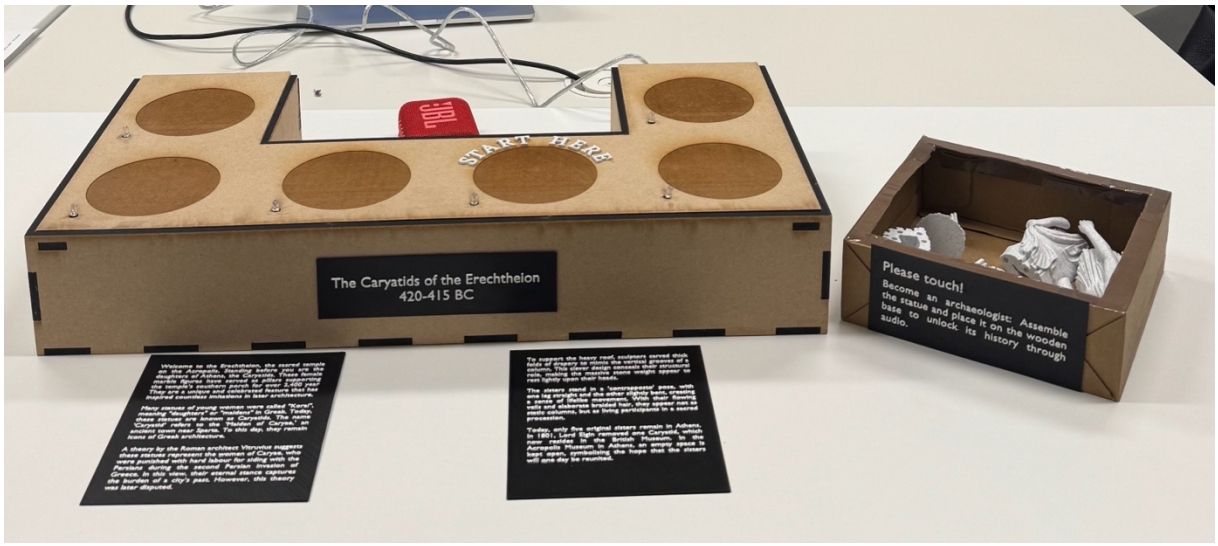


Figure 52: Set-up of Signage

4.2.6 Supports

To ensure the internal hardware remained secure during transport while maintaining the precise proximity required for the NFC reader to connect to the NFC tag, several custom mounting solutions were designed and fabricated.

Component Enclosures

To prevent damage to the circuitry while ensuring components remained removable for maintenance, dedicated enclosures were produced for the microcontroller and breadboards. A "Screwless Enclosure" designed by user_2685290945 was sourced from Bambu Mak-

erWorld. This provided a protective enclosure that could be glued to the base without exposing the Arduino to adhesive.

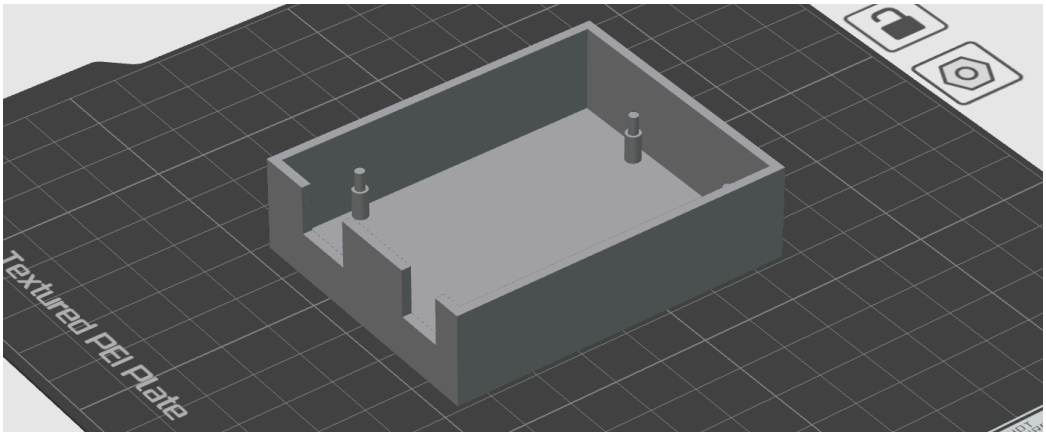


Figure 53: Arduino Enclosure

For the breadboards, custom cases were modelled in Blender based on calliper measurements of the two breadboard sizes: 59.7 x 169 x 10.5 mm and 87 x 59.9 x 10.5 mm. During the modelling process, two cubes were created to be slightly bigger than the breadboards. The cubes were hollowed by duplicating them, scaling them down, and lifting them. The final enclosure was then generated by applying a Boolean difference operation to subtract the internal volume from the primary cube.

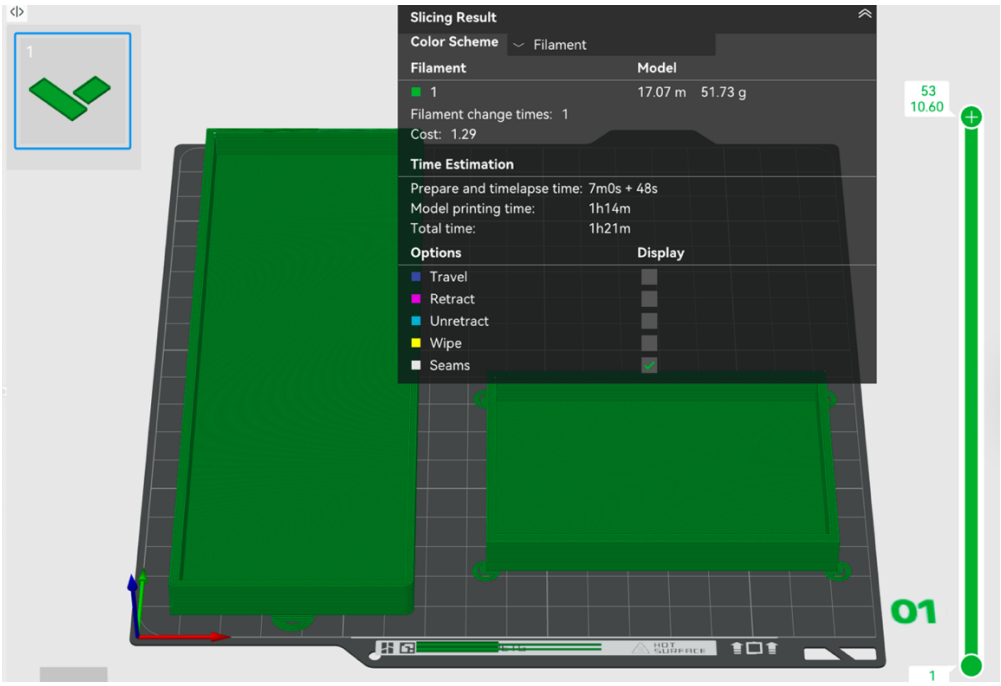


Figure 54: Slicer Settings for the Breadboard Enclosures

Both enclosures utilised brims during printing to prevent corner warping, ensuring a perfectly flat surface for glueing. All enclosures were printed with the SUNLU Black PLA+ filament and

used the default printing settings. The Breadboard print took an hour and 21 minutes and used 51.73 grams of filament. The Arduino enclosure took 35 minutes and 18 seconds and used 19.86 grams of filament.

NFC Reader Frames

The NFC readers required a specific elevation to ensure the tags could be read through the 6 mm MDF lid. The initial frame, measuring 132 x 86 x 10 mm, was created using a simple Boolean Difference operation in Blender to hollow out a solid cube. The top of the frame was then split into two parts using the same Boolean operation. The left half was lowered by the height of the NFC reader, whereas the right half stayed unchanged. This created a ledge on which the NFC reader case could later be glued. However, the resulting structure lacked stability and did not align perfectly with the base dimensions.

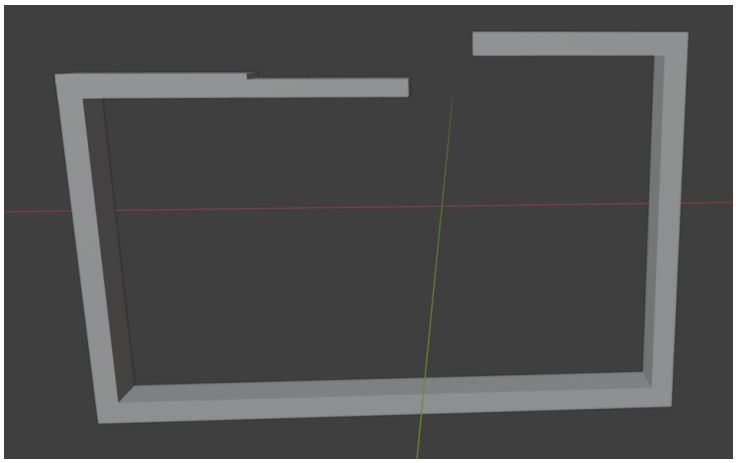


Figure 55: NFC Reader Frame (Version 01)

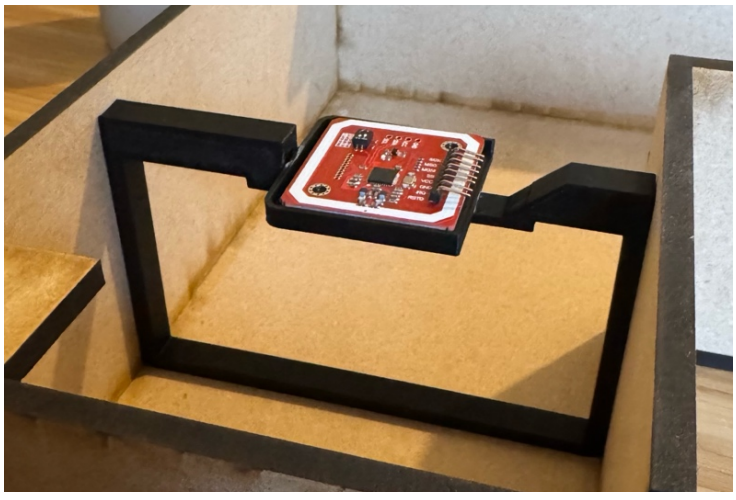


Figure 56: Final Version of NFC Reader Frame

The second and final frame was redesigned to a larger size of 138 x 86 x 10 mm. The top surface was thickened and indented to create a secure housing for the NFC reader case that was modelled after the finalisation of the frames (see Figure 56).

One frame had to be modified by importing the breadboard's enclosure and subtracting it from the frame's base to prevent physical collisions between components inside the base (see Figure 57). These frames were printed in SUNLU Black PLA+ over 4 hours and 38 minutes, using 155.69 grams of filament.

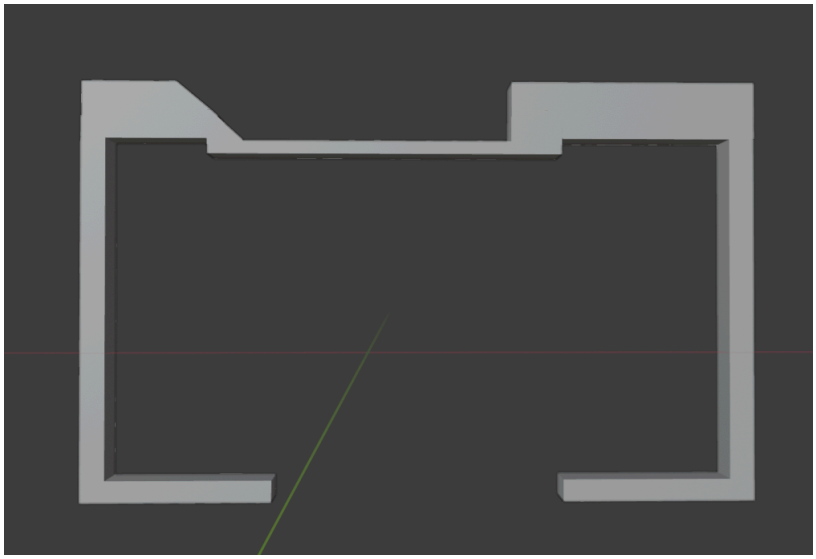


Figure 57: Modified NFC Reader Frame

NFC Reader Enclosure

The enclosure for the NFC readers required the most iterations. While the manufacturer's datasheet for the Elechouse PN532 V3 provided general dimensions, physical measurements were taken with callipers to determine the exact offset of the M3 mounting holes.

The enclosure was modelled in Fusion 360 with several key features to enable a friction-fit assembly. Firstly, a 0.2 mm tolerance was added to the inner dimensions to allow the reader to slide in snugly. Secondly, to avoid using screws, mounting pins were modelled in three variations (2.85 mm, 2.9 mm, and 3.0 mm diameters). This accounted for slight manufacturing variances in the NFC readers, ensuring every reader was held securely by friction. Additionally, pins featured a small fillet cut at the tips to guide them smoothly into the holes. To ensure the reader sits perfectly flat, internal levelling blocks were modelled at the base of the pins. The entire design was then combined into a single solid model to make it ready for 3D printing

The fabrication process took an hour and 16 minutes and used 37.46 grams of the SUNLU PLA+ Black filament.

Following fabrication, the individual NFC reader enclosures were permanently glued to the NFC support frames using super glue. This established a rigid, elevated assembly that maintained the exact distance required for the NFC sensors to communicate with the tags through the enclosure lid.

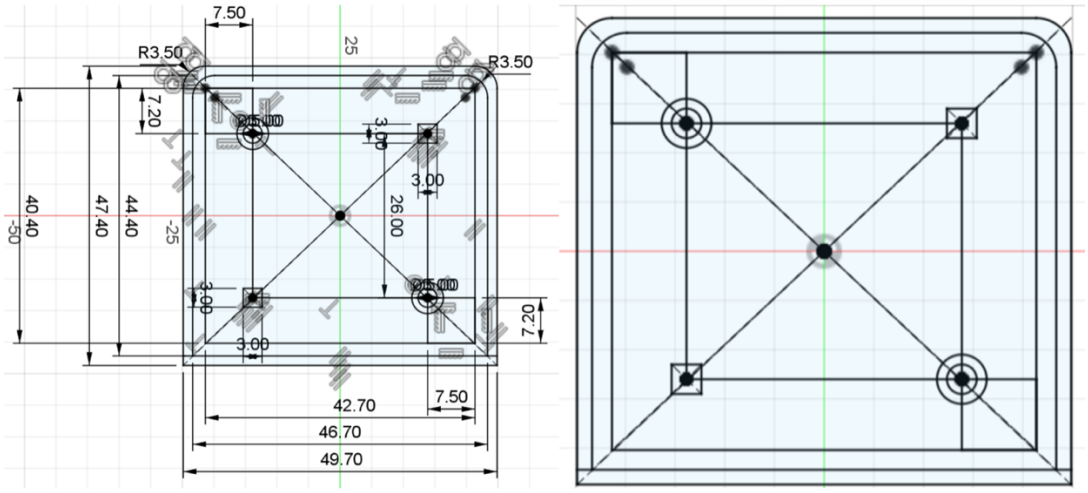


Figure 58: NFC Reader Enclosure in Fusion

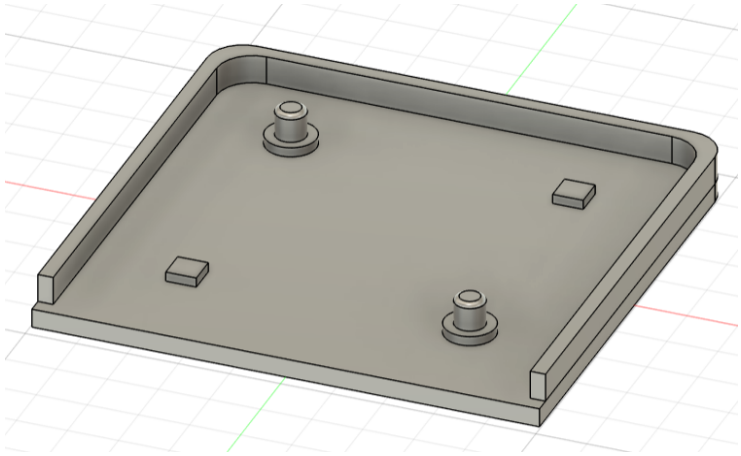


Figure 59: 3D Model of NFC Reader Enclosure

Structural Lid Supports

During assembly of the laser-cut base, it was observed that the lid was sagging in the centre. To resolve this, two 35 x 35 x 87 x mm support pillars were modelled and placed centrally. These pillars stabilised the lid, ensuring it remained flush with the walls and supported the weight of the replicas without sagging. The fabrication process took 2 hours and 56 minutes and used 124.03 grams of the SUNLU PLA+ Black filament. They were printed using the default

print settings, and brims were added to the edges of the pillars to ensure a smooth printing finish.

All internal supports were secured to the base using a combination of superglue and hot glue. This hybrid approach ensures the exhibit is robust enough for public handling and transport, while the modular case designs allow individual sensors to be removed or replaced if a technical failure occurs.

TABLE 7: TECHNICAL SUMMARY OF SUPPORTS

Component	Software	Filament	Print Time
Breadboard Cases	Blender	51.73g	1h 21m
Arduino Case	MakerWorld	19.86g	35m
NFC Enclosures	Fusion 360	37.46g	1h 16m
NFC Frames	Blender	155.69g	4h 38m
Lid Supports	Blender	124.03g	2h 56m

Figure 60: Supports placed within the Base (Note: Old LED supports included)

4.2.7 Auditory and Visual Output

The auditory output was generated using MiniMax Audio, an AI text-to-speech platform. The script was imported into the software, where a voice profile was selected and refined. Param-

eters such as pitch, cadence, and tonal warmth were adjusted to ensure the narration sounded natural and engaging rather than robotic.

Following the generation, the raw audio files were imported into Audacity for post-production. The following edits were performed to enhance the professional quality of the sound. Silence and unnecessary pauses were removed to maintain a steady narrative flow and minor adjustments were made to ensure consistency across all clips. Lastly, fades were applied to the beginning and end of some clips. The finalised audio was separated into six distinct files, labelled "Clip 1" through "Clip 6," ensuring seamless integration with the Processing code's naming conventions.

The visual assets were developed using Blender. To create an authentic museum atmosphere, the "Modern Design Room With Sunlight" scene by Robert Restu Pambudi was sourced via BlenderKit and modified. To enhance the natural aesthetic, a "Banana Plant" (Arsha AR) was added to the background. The central artefacts, the Caryatids, were integrated using a high-fidelity 3D model titled "Athens - Acropolis Museum – Caryatids" by Crazymaverickdc, sourced from Sketchfab under the appropriate creative licenses. This model served as the digital twin to the 3D-printed replicas used in the physical exhibit.

A multi-layered lighting strategy was implemented to simulate a gallery environment. The scene utilised a natural sunspot light included in the BlenderKit environment to provide foundational illumination. Additionally, two area lights were positioned to the left and right of the main scene to ensure the Caryatids were clearly defined and there were no harsh shadows. Lastly, a "Ceiling Lights" model from Re Models was used to house individual spotlights directed specifically at the statues to create museum-style lighting.

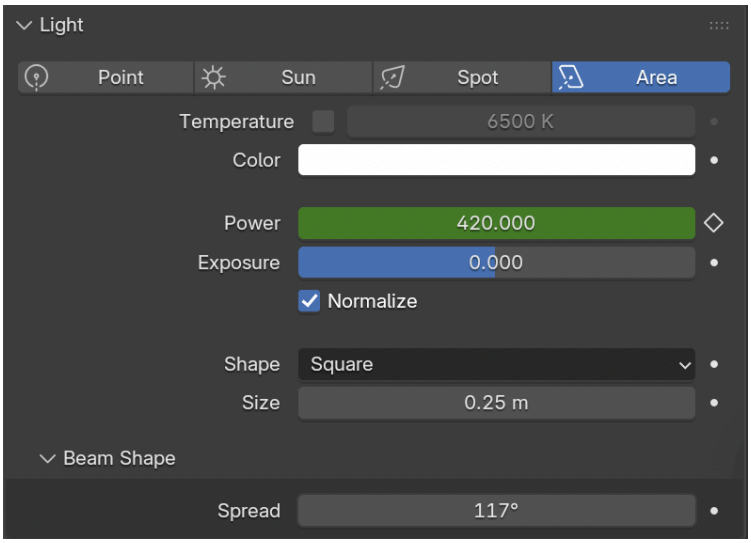


Figure 61: Area Light Settings

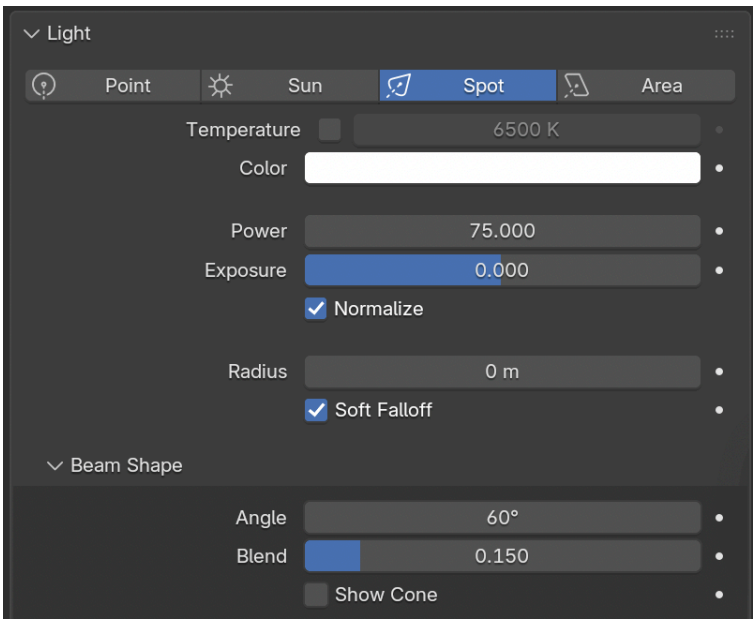


Figure 62: Spotlight Settings

The camera was positioned at a slightly elevated, downward-angled perspective, offset to the left. This static hero shot ensured that all five Caryatids remained centred and visible throughout the duration of the animation.

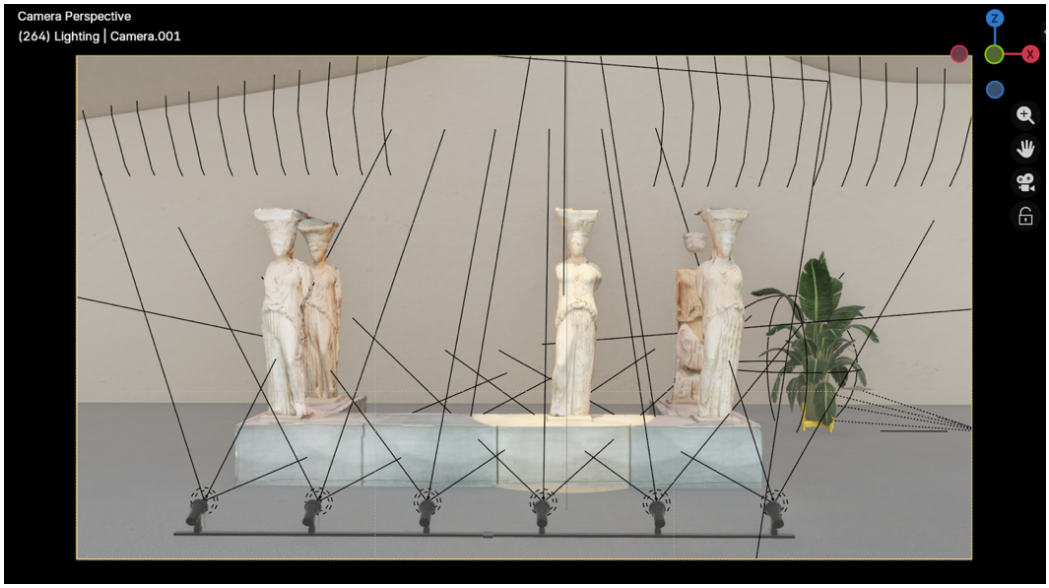


Figure 63: Camera Perspective

The narrative focus is guided by an animated spotlight. To maintain visitor engagement, each of the six animations was capped at 25 seconds. To determine at what frame, which action/movement should take place, handwritten logs were used to synchronise. By doing this, it was also possible to determine the desired frame rate that would provide the best balance between quality and render time.

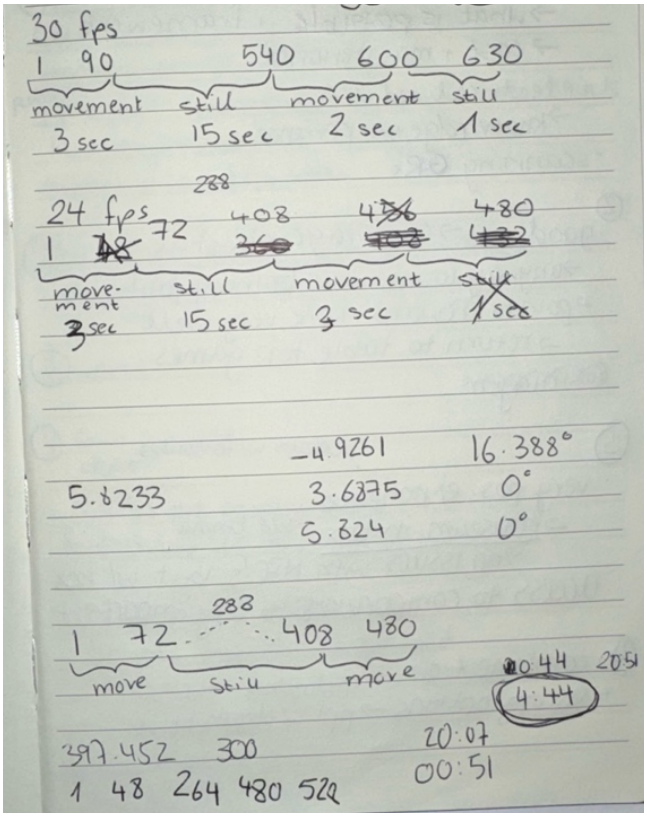


Figure 64: Handwritten Log

The animation followed a standardised keyframing logic at 24 frames per second (fps). The spotlight begins centred on the plant to provide a consistent starting point across all clips. Between frames 48 and 72, the spotlight moves to a specific Caryatid. Using the Graph Editor, subtle movements were added to the spotlight while it remained on the statue to keep the visual "alive" during the narration segments. The spotlight returns to its starting position to allow a smooth loopback to the Idle state. This was done six times for each Caryatid.

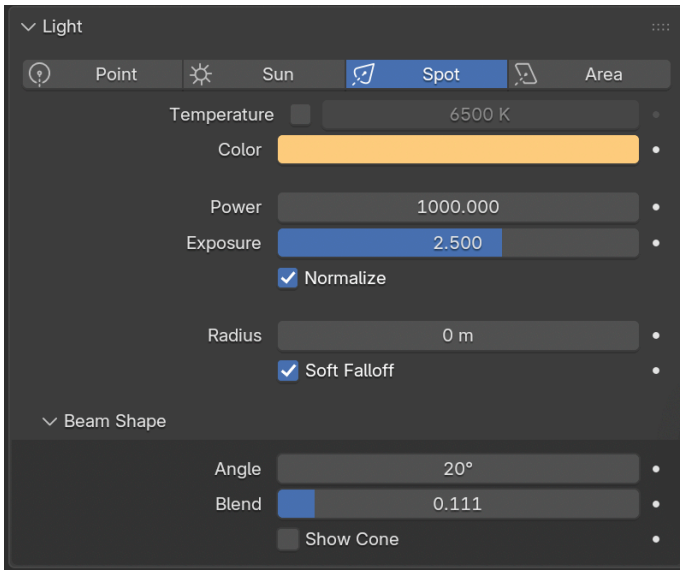


Figure 65: Animated Spotlight Settings

Figure 66: Spotlight in Scene

To mitigate the risk of software crashes during long render sequences, the animations were rendered as individual JPEG frames rather than a direct video file. This approach ensured that if a crash occurred, previously rendered frames were preserved.

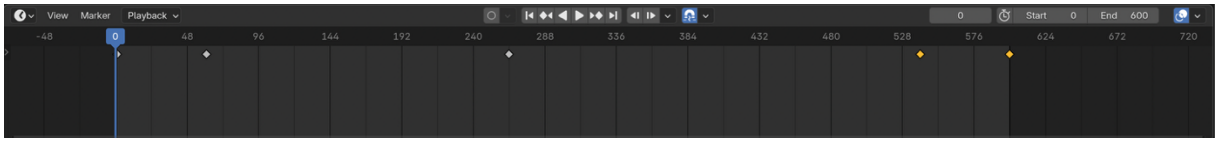


Figure 67: Keyframes for Animated Spotlight

The frames were then re-imported into the Blender Video Sequence Editor, where the audio file was synchronised with the visual animations. Specific animated segments were speed-ramped to ensure the spotlight transitions matched the audio's pace. The final clips were exported as MP4 files, optimised for playback within the Processing environment.

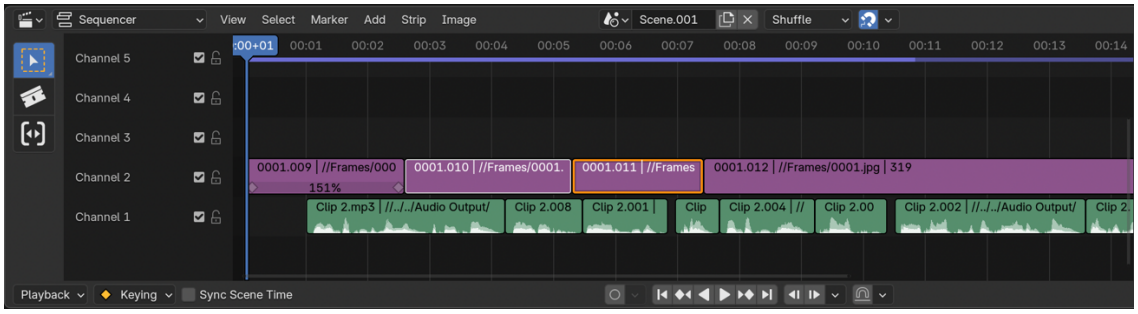


Figure 68: Screenshot of Blender Video Sequence Editor

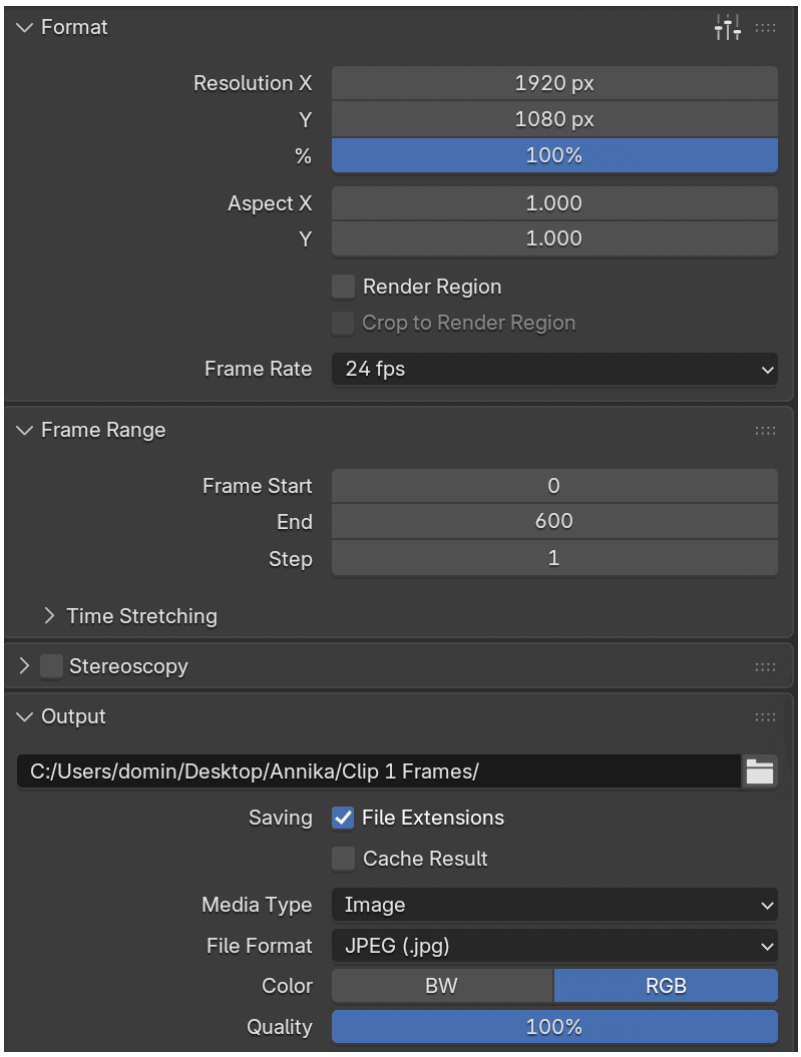


Figure 69: Blender Render Settings

4.3 Phase 3: Evaluation and Data Collection

Before beginning the user testing sessions, all participants were asked to read the Information Sheet and to sign the Consent Form digitally via a provided iPad. All user testing sessions were conducted on the UL Campus as stated in the ethics application.

4.3.1 Interactive Testing Environment

To evaluate the effectiveness of the interactive exhibit, a four-stage testing protocol was developed. This mixed-methods approach was designed to capture both quantitative metrics, such as dwell time and usability scores, and qualitative insights into the visitor experience.

Observation

Participants were asked to engage with the exhibit within a simulated museum environment. They were instructed to interact with the exhibit naturally, as they would in a public gallery,

concluding the session only when they felt they had reached a natural point of satiation or had acquired all desired information.

During this phase, the researcher performed a non-participatory observation, recording several key metrics. The first metric was the total duration of the interaction. This was timed to compare against the average interaction time of the static testing environment, providing data to test the engagement hypothesis. Notes were also taken regarding the ease of assembly, the sequence in which users engaged with specific attention points, and the order in which the replicas were placed. To ensure the validity of the behavioural data, there was no intervention or interaction between the researcher and the participant during this task.

Knowledge Quiz

Following the interaction, participants completed a digital knowledge quiz via Microsoft Forms (see Chapters 8.4 and 8.5). To evaluate the exhibit's pedagogical effectiveness, the quiz consisted of a mix of multiple-choice and short-answer questions. The content was derived from the travel journal, Greek Travel Tellers, "Caryatids: The Daughters of Athens" to ensure a comprehensive overview of the statues' origins and history. This assessment aimed to quantify the information retention facilitated by the tangible interaction.

System Usability Scales

To obtain quantifiable data on the interface's technical performance, users were asked to complete a System Usability Scale (SUS). This industry-standard 10-item Likert scale provides a reliable measure of the interaction's usability and learnability. By utilising a standardised metric, the project's results can be objectively benchmarked against other interactive museum technologies.

Semi-structured Interview

The final stage consisted of a 5- to 15-minute semi-structured interview. This enabled the collection of nuanced qualitative data on user enjoyment and perceived value. The interview questions were synthesised from the research objectives and the UK Arts Council's Researcher's Question Bank to ensure professional rigour. The Research Bank can be accessed from a link in the appendix (see Chapter 8.1). These conversations provided the "why" behind the quantitative scores, offering insights into the exhibit's emotional and cognitive impact. The session concluded by allowing participants to offer any additional unsolicited feedback. Later, the interviews were transcribed using Otter.ai and VoxBox, web services that automat-

ically transcribe audio files. Once they were transcribed, the transcripts were imported into MS Word for coding. Once the user testing sessions were concluded, the codes were combined to identify patterns and themes. These informed the continuation of this research and are presented in the results and discussion chapters (see Chapter 5 and Chapter 6).

4.3.2 Static Testing Environment

To provide a comparative baseline to the interactive exhibit, a three-stage testing protocol was developed. This mixed-methods approach was again designed to capture both quantitative metrics and qualitative insights into the visitor experience.

Observation

Again, participants were asked to observe the exhibit within a simulated museum environment. They were instructed not to touch the piece and to conclude the session only when they felt they had reached a natural point of satiation or had acquired all desired information.

Similarly to the interactive testing environment, the researcher conducted a non-participatory observation, recording the total duration of the interaction. To ensure the validity of the behavioural data, there was no intervention or interaction between the researcher and the participant during this task.

Knowledge Quiz

Following the observation, participants completed the same digital knowledge quiz.

Semi-structured Interview

The final stage consisted of a 5-to-10-minute semi-structured interview. This enabled the collection of nuanced qualitative data on user enjoyment and perceived value that could then be compared to the interactive exhibit. The interview questions were again synthesised from the research objectives and the UK Arts Council's Researcher's Question Bank to ensure professional rigour. The session concluded by allowing participants to offer any additional unsolicited feedback. The interviews were transcribed in the same manner as the interactive testing environment interviews.

4.3.3 Expert Interview

To ground the project's theoretical framework in practical museum operations, an expert interview was conducted with Maria Cagney, the Curator of Education and Outreach at the Hunt

Museum, Limerick. The interview took place in person within the museum's education wing. Given her role as an expert, the interview was conducted in a professional capacity. Consequently, anonymity was waived to allow for the direct attribution of her specialist insights to the project.

The interview followed a semi-structured format, consisting of eleven questions focused on museum learning and the integration of technologically enhanced exhibits. The primary objective of this interview was to validate the research goals through a real-world perspective, specifically regarding the longevity and sustainability of 3D-printed, tangible smart replicas.

Engaging with a professional curator allowed the research to move beyond academic hypotheses and address the practicalities of the museum landscape, such as visitor handling, maintenance requirements, and the durability of electronics. By incorporating this practitioner perspective, the study aimed to mitigate potential design limitations and ensure the final prototype met the rigorous standards of a public cultural institution. The session concluded with an open-ended discussion, providing the opportunity for additional expert feedback beyond the initial interview. The transcript was created with Otter.ai and can be seen in the appendix (see Chapter 8.10). This transcript was imported into MS Word for coding and assisted in answering the research question.

4.3.4 Improvements

After the user testing results were analysed, some frequently mentioned usability feedback was taken into consideration. The suggested improvements were listed and grouped into two categories: those within the scope and budget of this project and those out of scope. The suggested improvements that were out of scope or budget are be discussed in the Discussion (see Chapter 6.4).

In total, the following nine improvements were deemed in scope:

1. Implement on-screen visual prompts that mirror the physical LED light to assist users who are looking at the screen rather than the base.
2. Provide clearer messaging about the video's "default state" (the plant) and why the audio has stopped, reducing confusion during system "idle" or "error" moments.

3. Add explicit signage or visual cues to guide users on where to place the statue after the “START HERE” prompt and clarify that users can choose their own path rather than follow a linear sequence.
4. Include a sound when the statue is correctly placed to provide verification for users who may miss the small LED.
5. Program the green LED to turn off immediately once the video finishes playing.
6. Increase the size and prominence of the "Please touch!" sign and reorder the exhibit layout to follow a left-to-right reading pattern, placing the replica and "Please touch!" sign on the left to encourage natural tactile engagement.
7. Include a sign explaining the exhibit's mechanical workings and technology.
8. Improve the quality and aesthetic of the storage container for the statue pieces to match the high-quality 3D-printed artefact.
9. Address the issue of previous users leaving the statue assembled by adding a "Please disassemble" sign.

The first three improvements were realised by changing the “idle” image that was displayed on the screen before and in between videos.

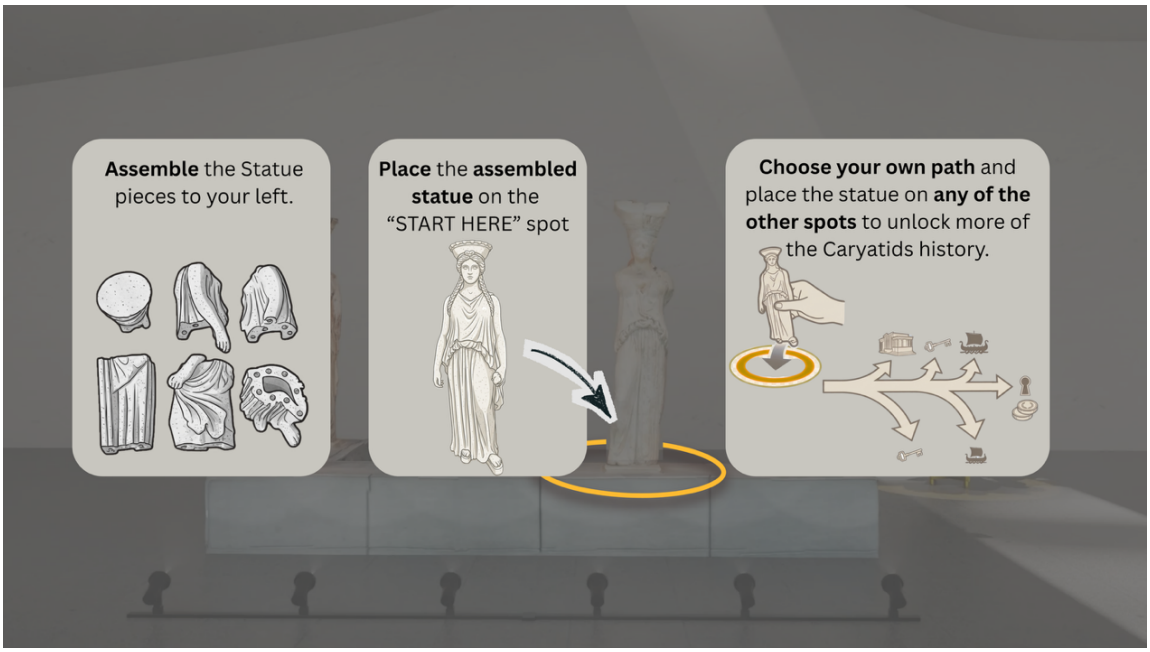


Figure 70: Improved "idle" image

Before visitors interact with the exhibit, an image is displayed instructing them to assemble the statue and place it on the “START HERE” spot. Lastly, they are told to choose their own paths and place the state on any of the other spots to unlock more of the artefacts’ history. This directly addresses the first three suggested improvements. However, the “START HERE”

instruction might confuse visitors if it is displayed between videos, while they are already engaging with the exhibit. To address this, a second image was created to be displayed between videos. In the second image, a “No Statue Detected” prompt appears, providing further instructions for engaging with the exhibit. The “choose your own path” instructions are repeated. After 30 seconds, the image changes back to the “idle” image, assuming the previous visitor has left the exhibit.

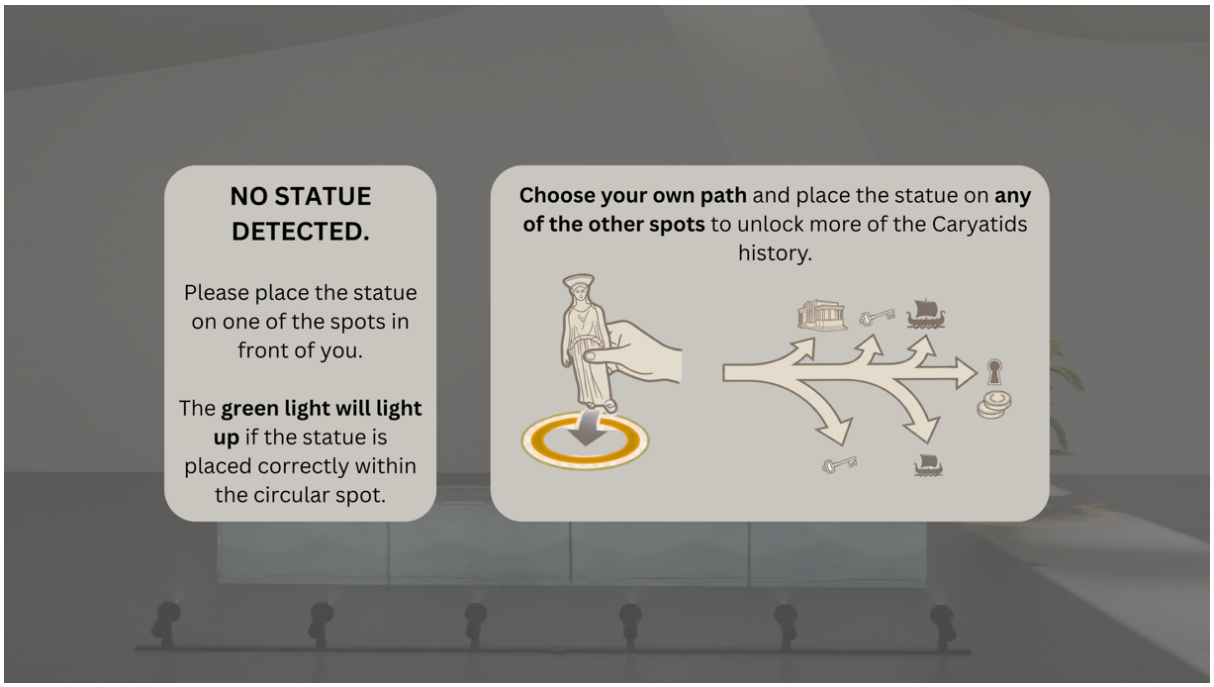


Figure 71: Added Instruction screen

These graphics were created using Canva and Gemini. Gemini was used to generate the smaller graphics of the statue pieces, the statue and the “choose your own path” graphic.

To address the next two suggested improvements, the code had to be adjusted. The first change was made to the processing code to add a sound when the statue is correctly placed, providing visitors with verification. A sound was selected from the elevenlabs.ie website called “Gentle ding for saved settings confirmation”. The link to access this sound can be found in the appendix.

Every time the Processing code detects a "START_", the ping sound plays, providing the visitor with audio feedback that they have placed the statue correctly.

```
try {
  pingSound = new SoundFile(this, "ping.mp3");
  println("ping.mp3 loaded.");
} catch (Exception e) {
  println("!!! Error loading ping.mp3: " + e.getMessage());
}
```

Figure 72: Code Changes in Processing

```
// play success ping
  if (pingSound != null)
{     pingSound.play();
    }
```

Figure 73: Code Changes in Processing

Next, the Arduino and Processing code were modified to have the green LED turn off immediately once the video finishes playing. This gives the visitor another form of feedback and signals that they need to take action to continue with the exhibit. When a video ends, processing sends a command, "LED_OFF_", to the Arduino through its serial connection. The added code continuously checks whether the Arduino has received a message via the Serial port. It looks for this LED command followed by the reader ID. Once it identifies the correct reader using the reader ID, it turns off the associated LED and temporarily locks the reader, so it doesn't immediately re-trigger, as the tag is likely to remain on the reader. This locked-out state is reset after the tag is removed, as handled by ProcessFailure(). The added code snippet ensures that once a story finishes playing, the exhibit resets to its instruction screen.

```
// Read for Light off signal on completion of video
if (Serial.available() > 0) {
  String cmd = Serial.readStringUntil('\n');
  cmd.trim();
  if (cmd.startsWith("LED_OFF_")) {
    int id = cmd.substring(8).toInt();
    int index = id - 1;
    if (index >= 0 && index < numReaders) {
      digitalWrite(pins[index], LOW);
      lockedOut[index]     = true;
      tagDetected[index]   = false;
      activeReader         = -1;
      missCount[index]     = 0;
    }
  }
}
```

Figure 74: Changes to the Arduino code

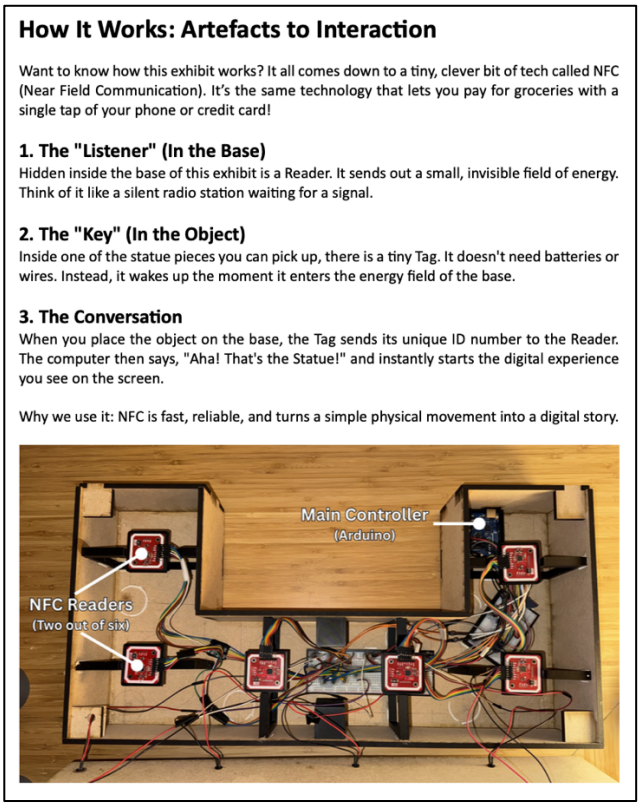
The next and most repeated suggested improvement is to increase the size and prominence of the "Please touch!" sign and reorder the exhibit layout to follow a left-to-right reading pattern, placing the replica and "Please touch!" sign on the left to encourage natural tactile engagement before the reading of the information sign. This was combined with the improvement to address the issue of previous users leaving the statue assembled by adding a "Please disassemble" sign.

In Blender, a 170 x 175 mm plane was created. The text from the “Please touch!” sign was copied, pasted and scaled onto the new plane. The text was roughly doubled in size.
Below the text, a new instruction was added: “Please disassemble after you are done.” The “Please disassemble” instruction was increased to match the size of the “Please touch!” instruction.

Figure 75: Old “Please touch!" sign (left) and new "Please touch!" sign (right)

Additionally, a sign holder was 3D-printed to allow the sign to stand upright rather than lie flat on the table. This further increased the sign’s visibility. The sign stand was taken from the Bambu Studio MakerWorld. It is called “Sign Stand (2 Versions)” and was uploaded by Mr.Cheez541. The link to access this model can be found in the appendix. This sign was scaled along the x-axis by 219%. This made the length of the sign stand match the length of the sign, ensuring a secure fit.
Additionally, another sign was added to explain the exhibit's mechanical workings and technology. This was done as almost every user testing participant asked follow-up questions after the testing concluded about how the exhibit worked, with one participant mentioning it dur-

ing the interview. A PDF was created that explains the technology behind the triggering mechanism in simple language. The sign is laminated to increase longevity and placed next to the exhibit for visitors to read if they are interested in its workings.



How It Works: Artefacts to Interaction

Want to know how this exhibit works? It all comes down to a tiny, clever bit of tech called NFC (Near Field Communication). It's the same technology that lets you pay for groceries with a single tap of your phone or credit card!

1. The "Listener" (In the Base)
Hidden inside the base of this exhibit is a Reader. It sends out a small, invisible field of energy. Think of it like a silent radio station waiting for a signal.

2. The "Key" (In the Object)
Inside one of the statue pieces you can pick up, there is a tiny Tag. It doesn't need batteries or wires. Instead, it wakes up the moment it enters the energy field of the base.

3. The Conversation
When you place the object on the base, the Tag sends its unique ID number to the Reader. The computer then says, "Aha! That's the Statue!" and instantly starts the digital experience you see on the screen.

Why we use it: NFC is fast, reliable, and turns a simple physical movement into a digital story.

Figure 76: "How It Works" sign

Lastly, the quality and aesthetics of the storage container for the statue pieces needed to be improved to match the high quality of the rest of the exhibit. For this, a vector drawing of a box using finger joints was created in Affinity Vector. The box is made out of 6 mm MDF and has an opening at the top. The pieces were laser-cut using the same settings as the base, as this setup proved successful.

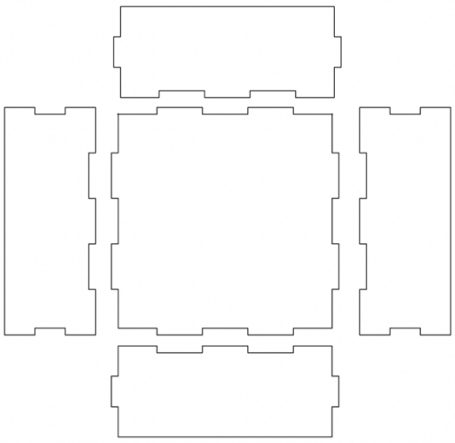


Figure 77: Vector Drawing of the Container for the Statue Pieces

Figure 79: Laser-Cut Box for Statue Pieces (Top View)

Figure 78: Laser-Cut Box for Statue Pieces

Figure 80: Laser-Cut Box with Statue Pieces

5 Results

5.1 Quantitative Data

5.1.1 Visitor Engagement

Visitor engagement was measured primarily through dwell time (time spent interacting with the testing exhibits) and a Likert Scale. Data was collected from 20 observations and interviews, split equally between a Static Display (Group A) and an Interactive Display (Group B). The Static Display included a scaled-down 3D-printed replica of the original Caryatids as they are displayed in the Acropolis Museum, with an information text. Details on the execution are available in Chapter 4.3.2. The Interactive Display included the interactive prototype. As previously mentioned in Chapter 4.3.1, there was no intervention or interaction between the researcher and the participant during the observation to ensure the results were not influenced. The participants received only one instruction before starting the observation: to conclude the session when they felt they had reached a natural point of satiation or had acquired all desired information.

TABLE 8: DWELL TIME

No. of Observation	Type of Observation	Dwell Time
01	Interactive	280 seconds
02	Interactive	275 seconds
03	Interactive	351 seconds
04	Interactive	209 seconds
05	Interactive	285 seconds
06	Interactive	209 seconds
07	Interactive	289 seconds
08	Interactive	280 seconds
09	Interactive	272 seconds
10	Interactive	246 seconds
11	Static	72 seconds
12	Static	54 seconds
13	Static	170 seconds
14	Static	89 seconds

15	Static	120 seconds
16	Static	165 seconds
17	Static	70 seconds
18	Static	109 seconds
19	Static	61 seconds
20	Static	142 seconds

The Interactive Replica recorded an average dwell time of 269.6 seconds. The Static Display recorded an average of 105.2 seconds. This represents a 156.3% increase in engagement time for the interactive group. The least-engaged interactive participants (209 seconds) still spent more time at the exhibit than the most-engaged static participants (170 seconds).

TABLE 9: DWELL TIME COMPARISON

Type of Observation	**Average Dwell Time**	**Minimum**	**Maximum**
Static Display	105.2 seconds	54 s	170 s
Interactive Replica	269.6 seconds	209 s	351 s

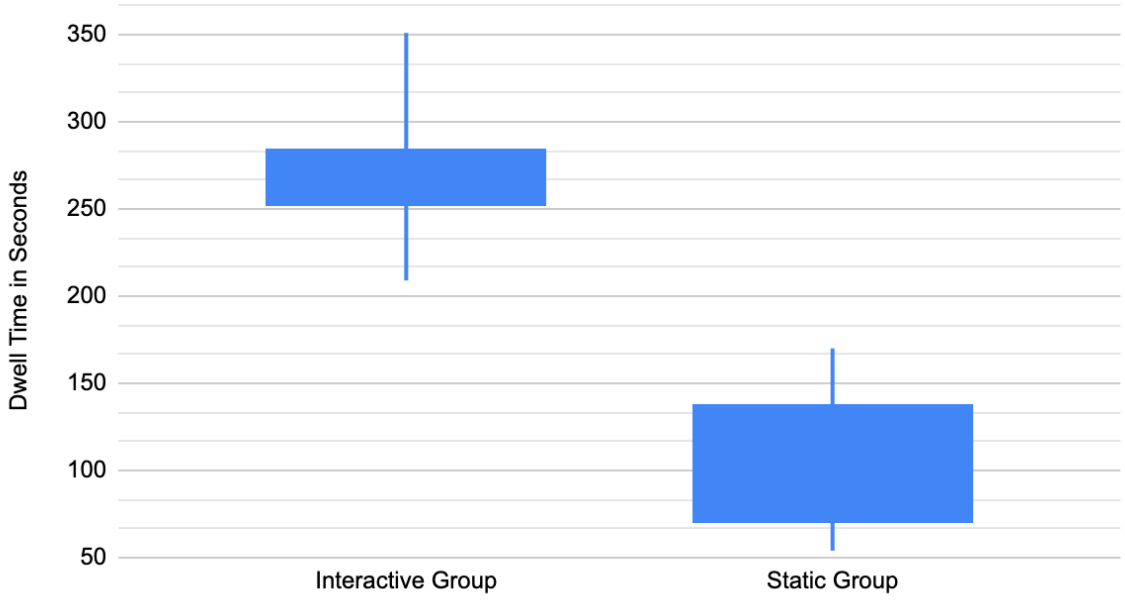


Figure 81: Dwell Time: Interactive vs Static Group

An unpaired t-test (independent-samples) was performed to evaluate the impact of the exhibit type on participant engagement, measured by dwell time. The results revealed a statistically significant difference between the two groups in engagement levels.

$$t(18) = 8.7276, p < 0.0001$$

The difference is considered extremely statistically significant. Participants in the interactive group spent considerably more time engaging with the display compared to those in the static group. These results provide strong evidence that the interactive elements significantly increased user dwell time, indicating higher engagement.

During the participant interviews, both the interactive and the static group were asked a Likert-scale question to provide comparative data on enjoyment. All participants were asked to rate their enjoyment on a scale of 1 to 5, 5 representing “Excellent” (see Table 10).

TABLE 10: SUMMARY ENJOYMENT SCORES

Participant	Group	Rating
01	Interactive	5
02	Interactive	5
03	Interactive	4
04	Interactive	5
05	Interactive	5
06	Interactive	5
07	Interactive	5
08	Interactive	4
09	Interactive	5
10	Interactive	3
11	Static	3
12	Static	2
13	Static	3
14	Static	3
15	Static	5
16	Static	2.5
17	Static	3

18	Static	3
19	Static	3
20	Static	3

In the interactive group, 7 out of 10 participants gave a perfect score of 5, giving an average rating of 4.6 out of 5. In contrast, the static group reported a decline in interest over time, with one participant (P11) noting that their enjoyment dropped from 4 to 2 during the session. They gave an average rating of 3 out of 5. This demonstrated a 53.33% increase in enjoyment from the static group to the interactive group.

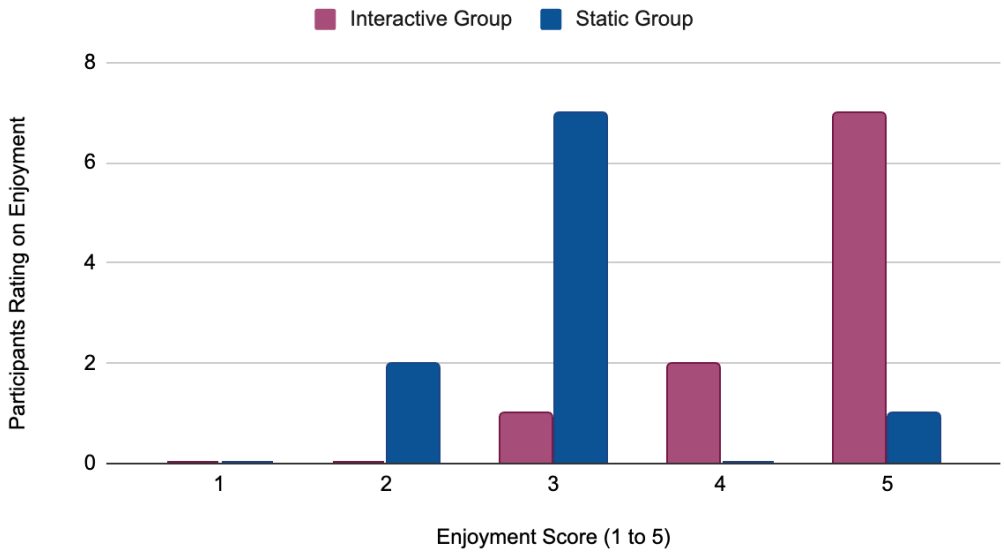


Figure 82: Engagement Scores: Interactive vs Static Group

5.1.2 Information Recall

Following the observation, participants completed an 8-question knowledge quiz to assess their information recall. The list of questions and their correct answers can be viewed in the appendix (see Chapters 8.4 and 8.5).

TABLE 11: SURVEY ANSWERS CORRECT VS INCORRECT

Question	Static Correct	Interactive Correct
Q1	7/10	8/10
Q2	8/10	10/10
Q3	7/10	9/10
Q4	6/10	9/10
Q5	5/10	8/10

Q6	1/10	7/10
Q7	6/10	6/10
Q8	7/10	6/10
TOTAL	**47/80**	**63/80**

On average, participants in the static group correctly answered 4.7 out of 8 questions (58.75%), resulting in a mean error rate of 3.3 questions (41.25%). In contrast, the interactive group correctly answered 6.3 out of 8 questions (78.75%), resulting in a mean error rate of 1.7 questions (21.25%). This represents a significant improvement in knowledge retention through the use of the Tangible Smart Replica.

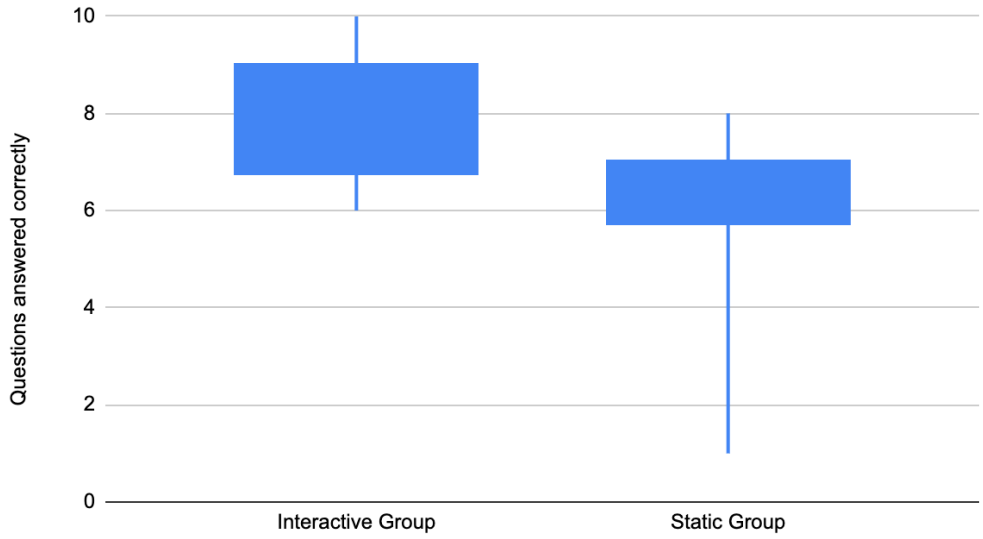


Figure 83: Information Recall: Static vs Interactive Group

Specific questions highlighted clear gaps in retention between the two groups. Both groups performed well on Question 2, the function of the statue. The interactive group achieved 100% accuracy on this question, while the static group achieved an 80% accuracy, their highest accuracy across all questions. However, Q6, the punishment of the women from Caryae, showed the greatest disparity. The interactive group achieved 70% accuracy, whereas the static group achieved only 10%. This represents a 600% increase in correct responses for this question, suggesting that the interactive elements were highly effective in communicating that specific concept. Participants in the interactive group showed a 34% improvement in overall information recall.

To assess the educational impact of the exhibit types, an unpaired t-test was performed comparing the quiz scores of the two groups. The analysis revealed a statistically significant difference in learning outcomes.

$$t(14) = 2.17, p = 0.05$$

Participants in the interactive group achieved higher quiz scores (M = 7.88, SD = 1.46) compared to those in the static group (M = 5.88, SD = 2.17). These findings suggest that the interactive exhibit was more effective at facilitating knowledge retention than the static display.

5.1.3 System Usability

The interactive group completed the System Usability Scale (SUS) to evaluate the prototype's interface and physical interaction. Participants rated 10 standardised questions on a scale of 1 to 5. Following the industry-standard calculation method:

> *" For each of the odd numbered questions, subtract 1 from the score.*
>
> *For each of the even numbered questions, subtract their value from 5.*
>
> *Take these new values which you have found, and add up the total score. Then multiply this by 2.5." (Thomas, 2015)*

While the final score is represented out of 100, it is a ranked score rather than a percentage. The individual results for the ten interactive participants are detailed in Table 12.

TABLE 12: SYSTEM USABILITY SCALE RESULTS

Participant	Responses	Total Points	Final SUS Score
1	5, 1, 5, 1, 5, 1, 4, 1, 5, 1	39/40	97.5/100
2	4, 2, 5, 1, 5, 1, 4, 2, 5, 2	35/40	87.5/100
3	5, 1, 5, 1, 5, 1, 5, 1, 5, 1	40/40	100/100
4	4, 1, 5, 1, 5, 1, 5, 2, 5, 1	38/40	95/100
5	5, 2, 5, 1, 5, 1, 5, 1, 5, 1	39/40	97.5/100
6	5, 2, 5, 1, 5, 2, 5, 1, 5, 1	38/40	95/100
7	5, 1, 5, 1, 5, 1, 4, 1, 5, 1	39/40	97.5/100
8	5, 2, 5, 2, 5, 1, 4, 1, 5, 1	37/40	92.5/100
9	5, 1, 5, 1, 5, 1, 5, 1, 5, 1	40/40	100/100
10	4, 1, 5, 1, 3, 1, 4, 1, 3, 1	34/40	85/100
Mean		37.9	94.75

The interactive exhibit achieved a mean SUS score of 94.75. Every participant scored the system at 85 or above, which gives the prototype a Grade A, well exceeding industry standards (Thomas, 2015).

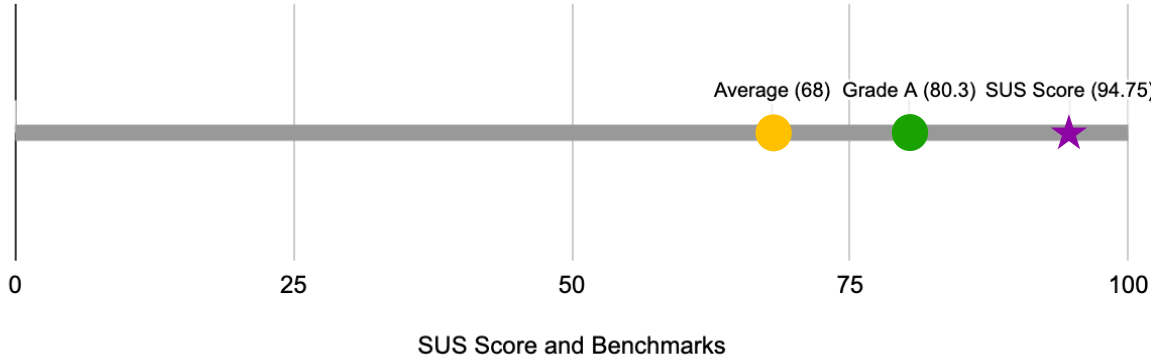


Figure 84: SUS Score Ranking: Interactive Exhibit vs Benchmarks defined by (Thomas, 2015)

5.1.4 Quality and Intuitiveness Scores

Following the Knowledge Quiz, all 20 participants took part in individual interviews lasting 5 to 15 minutes. During those interviews, the interactive group was asked two additional Likert-scale questions. They rated the quality of the statue's weight and material, and how intuitive they found the statue assembly. Participants gave the weight and material quality an overall rating of 4,7 out of 5 (see Table 13). Further comments made regarding the quality of the statue can be found in Chapter 5.2.3.

TABLE 13: QUALITY OF THE STATUE'S WEIGHT AND MATERIAL OUT OF 5

Participant	Rating
01	5
02	4
03	4
04	5
05	5
13	5
14	5
15	4
16	5
20	5

The intuitiveness of the statue assembly received the same rating, 4.7 out of 5 (see Table 14). Further comments made regarding the intuitiveness of the statute assembly can be found in Chapter 5.2.3.

TABLE 14: INUITIVENESS OF THE STATUE ASSEMBLY OUT OF 5

Participant	Rating
01	5
02	5
03	5
04	4
05	4
13	5
14	5
15	4
16	5
20	5

5.2 Qualitative Data

5.2.1 Longevity and Sustainability

While the data speaks for itself, an interview was conducted with Maria Cagney, Curator of Education and Outreach at the Hunt Museum, to validate the prototype's professional viability and its potential for long-term museum integration.

Before assessing the prototype directly, Cagney outlined the primary barriers museums face when implementing interactive exhibits. She identified these as logistical and financial in nature rather than technological. A significant knowledge gap exists between game designers and museum educators. Staff frequently feel unfamiliar with what is possible, and internal technical knowledge proves unsustainable when concentrated in a single individual. When those single individuals leave, those skills "walk out the door" with them. Maintenance reliability was described as a persistent operational concern, with digital interactives regularly requiring Service Level Agreements (SLAs) with external companies. Lastly, funding was characterised as almost entirely project-based, meaning interactive exhibits are rarely budgeted for systematically across an institution and often rely on external funding to be realised.

When given the prototype, Cagney described the 3D-printed puzzle as “a brilliant project” and as “look[ing] engaging.” She confirmed “[t]here's huge potential” for incentivising learning with the prototype. Her assessment was grounded in direct institutional experience. Cagney noted that the museum had used point-reward and game-based systems in school programmes with strong results, and that encouraging "playfulness" in a museum environment should be taken seriously as a pedagogical strategy. She referenced the museum's existing chessboard installation as evidence that game-based learning is already being demonstrated effectively in a museum context.

Regarding sustainability, Cagney noted that the puzzle format is highly adaptable. It can be scaled in size or complexity to suit different age groups. She also identified a concrete potential application, noting that the puzzle format could be integrated into the museum's existing educational loan box programme for schools, where it would complement existing replica object sets.

> *“it would be a really lovely addition to an existing resource like that” (Cagney, 2026)*

She further outlined specific criteria required for a 3D-printed replica to withstand a high-traffic museum environment. Firstly, visitor safety is a primary concern. Cagney noted that raw PLA can have “rough or sharp edges”. Thorough sanding and coating are mandatory to prevent injuries. The physical weight of a replica is tied to its perceived authenticity. High infill settings or internal weights are required to ensure the experience is memorable. Cagney further mentions that museums often lack internal technologists. The use of standard, easily sourceable components is essential to avoid shipping delays. Additionally, she states that while resin is more durable, its cost can be challenging. PLA remains a practical choice provided it is properly post-processed and reinforced. Lastly, she notes that the system must not rely on just one output. It requires a combination of audio, visual, and text to meet the requirement of "giving people different options" for interacting, including people with disabilities.

Cagney also confirmed that the Hunt Museum's experience with NFC technology across its existing sensory exhibitions has been broadly positive, noting that the technology itself has caused no significant problems and that reliability issues have consistently originated in surrounding hardware rather than the NFC components themselves.

The interview further established that the physical environment is as vital as the digital interaction. Cagney flagged height-adjustable display surfaces as essential for wheelchair accessibility, citing the museum's own use of electric height-adjustable tables in its sensory exhibitions. She also recommended providing seating and rest stations to prevent visitor fatigue, noting from personal experience that museums can become physically overwhelming. Table 15 summarises the expert requirements for a professional exhibition.

TABLE 15: PROFESSIONAL EXHIBIT REQUIREMENTS

Feature	Requirement	Purpose
Height	Height-adjustable tables	To accommodate wheelchair users, people with mobility aids and children.
Rest Stations	Integrated seating	To combat museum fatigue and accommodate people with disabilities.
Modality	Combined audio, visual, and text	Options for neurodivergent or disabled visitors and different types of learners.
Feedback	Visual/auditory reward	To incentivise completion and confirm success.
Robustness	Full functionality always	To prevent negative impressions of the institution.

Ultimately, Cagney's insights validate the prototype as a professionally viable tool. Considering Cagney's design requirements, the project directly addresses the museum's need for sustainable, locally maintainable technology that does not "walk out the door" with a single expert.

5.2.2 Usability Feedback

The qualitative data from participant interviews and observations identified both the prototype's successful functional implementations and its primary points of friction. This section details the behavioural patterns observed during the initial interaction phase, complemented by feedback provided during the post-interaction interviews.

These findings directly informed several design enhancements aimed at clarifying system states and streamlining physical interactions. While key improvements were integrated into the final prototype (as detailed in Chapter 4.3.4), certain features were deemed out of scope

due to technical and resource constraints. A comprehensive list of these requirements is provided in Chapter 6.4.

Many participants commented on the overall professionalism of the exhibit and the prototype in particular. In terms of system simplicity, Participant 05 described the overall system as being as simple as it could be, which they identified as a positive for broad museum accessibility. This simplicity extended to physical guidance, where Participant 02 noted that the visible gaps in the partially assembled sculpture acted as a natural guide during assembly, working alongside the magnetic connections to direct the process.

The materiality of the 3D-printed replica also received significant praise. Several participants commented on the tactile qualities of the 3D-printed replica, describing it as hefty and premium-feeling (e.g. P01, P04, P20). Participant 20 explicitly stated that the quality of the print was "noticeably better" than examples they had encountered in other settings. The weight of the statue was cited as a crucial factor in establishing a sense of professional authenticity. Additionally, Participant 04 described the experience as professional and engaging. The system's affordances clearly signalled its purpose. Most participants identified the assembly logic immediately upon approach, with Participant 04 observing that although pieces could be placed incorrectly, the system made it clear when they had been placed correctly.

Regarding system feedback, several participants noted that the green LED indicator and auditory response provided a clear connection between physical interaction and digital output. However, some participants did not notice the LED. For example, Participant 20 directed their attention toward the screen rather than the base of the exhibit and therefore missed the LED feedback. Participant 15 observed that the system triggered a response upon placement of the feet piece alone, rather than upon the statue's full assembly. Concerning learning curves and friction, some participants observed minor mechanical difficulties during assembly, including an instance where a statue's arm obstructed the placement of a skirt piece. Nevertheless, all participants successfully assembled the statue. Participant 02 specifically emphasised that the incorporation of magnets facilitated the process. Additionally, Participant 05 noted that the magnetic assembly removed any concerns regarding the object falling apart.

Regarding the permission barrier, the majority of participants did not interact with the physical replica until they had read or even seen the "Please touch!" signage. However, Participant 04 indicated that they did not notice the sign, asserting that the purpose of the object was

evident from its appearance alone. Regarding the sequence of interaction, Participant 14 noted that a natural left-to-right reading pattern guided them towards the text panels prior to engaging with the physical replica.

Considering user divergence, the majority of participants engaged with the physical assembly and audio-visual content simultaneously, whilst some participants read all written information before attempting assembly (e.g. P05). Participant 13 noted that had they known the audio narrative covered the same content as the information text, they would not have read the panels in full. Lastly, participants expressed technical curiosity. Participant 15 noted that the NFC mechanism prompted interest in the system's underlying technology and suggested that a small amount of explanatory content about it would benefit some visitors.

In summary, the usability results indicate that the prototype achieved a high level of physical and cognitive accessibility, as evidenced by the consistently high scores for materiality and intuitiveness. While minor technical friction points, such as LED visibility and specific audio sequences, were identified, they did not prevent successful user engagement.

5.2.3 Engagement, Retention, and Accessibility

Further analysis of qualitative interview and observation data revealed a consistent pattern across both groups, with physical interactivity emerging as a decisive factor in shaping engagement, retention, and accessibility. Four themes were identified during analysis: tactile engagement, engagement decline, information retention, and accessibility.

Tactile Engagement

For the interactive group, physical interaction transformed the learning process from passive reception into active discovery. A central theme was tactile anchoring, where handling the replica helped participants connect the physical action to the historical content. Participant 16 noted that doing something while receiving information made the information significantly more memorable than simply standing and observing. Participant 20 described how having something tangible in their hands helped link the body to the brain. Participant 01 also reported a phenomenon of accidental learning, in which the gamified assembly reduced perceived cognitive load to the point that the educational content felt as though it had snuck in. The free-navigation structure further contributed to a sense of agency, with Participant 01

comparing the experience to turning the pages of a book rather than passively receiving information, which was supported by Participant 14.

Engagement Recline

The static group, by contrast, followed a pattern of high initial interest and a rapid decline in engagement. Participants frequently described the experience as something they would see in a museum, keep moving, and not remember afterwards (P09). Several participants identified reading barriers as the primary cause of museum fatigue and a decline in engagement. Long text panels prompted a shutting-off response (P07, P12, P18), in which visitors disengaged entirely from the learning aspect. A further theme within this group was the separation of interest from engagement. Participant 19 drew a clear distinction between finding the subject matter interesting and its delivery unengaging, a distinction that did not arise in the interactive group.

Information Retention

Regarding retention, the two groups diverged sharply. Within the interactive group, physical interaction was consistently reported to produce more durable memory. Participant 02 noted that the experience lingered after completion, in contrast to passive visits where content is quickly forgotten (P07). The assembly process and audio narrative were also reported to support closer engagement and to help visitors distinguish between the individual components of the exhibit, such as the drapery of the statue (P01, P04, P13). Participant 01 reported that the educational content felt absorbed without the conscious effort typically associated with learning. Participant 14, who read the information text before the corresponding audio triggered, described the resulting double exposure as producing stronger recall than a typical museum visit. Within the static group, difficulty retaining content was widely reported despite participants feeling they were learning during the experience. A disconnect that Participant 11 described as being unable to recall anything immediately afterwards. This is directly reflected in the results from the Knowledge Quiz detailed in Chapter 5.1.2.

Accessibility

The interactive format also demonstrated broader accessibility benefits. The multimodal structure, combining tactile assembly, spoken narration, visual supports and written text, accommodated participants who found dense written content difficult to process (P02, P13).

Participant 06 further emphasised that people learn in different ways and that static exhibits restrict these natural learning patterns, but the interactive version supports a wide range of learning types. The spoken narration was identified as particularly beneficial for visitors who are easily distracted or do not readily engage with long written texts (P05). The synchronised audio and text were noted to support visitors who find dense written content difficult to process, and the visual and tactile components provided an additional fallback for visitors for whom audio or text alone did not fully register (P02, P13). The multimodal approach also allows multiple visitors to engage with the exhibit simultaneously rather than waiting to read a single plaque (P13).

These findings collectively suggest that physical agency is not merely a novelty feature but a meaningful mechanism through which museum exhibits can support diverse visitors and produce more durable learning outcomes.

5.3 Cost Breakdown

To ensure the feasibility of this project for museum integration, the total cost was strictly capped at €200. This threshold was informed by primary research and an interview with the Curator of Education and Outreach at the Hunt Museum, Maria Cagney.

During the interview, Cagney noted that a previous acquisition of six 3D-printed exhibition pieces cost approximately €2,000, resulting in a unit price of roughly €333. While she indicated that this was on the lower end of industry quotes, there was a level of uncertainty regarding the exact figures.

To account for this variability and to ensure the solution remains accessible to smaller institutions with limited funding, the budget was intentionally reduced. By delivering a functional prototype for €197.77, the project demonstrates that high-quality, interactive exhibits can be produced at a significantly lower price point than current commercial alternatives, thereby enhancing the sustainability of 3D-printed museum technology.

TABLE 16: PROJECT COST BREAKDOWN

Category	Component	Specification	Price
Hardware	Microcontroller	Arduino Uno WiFi REV2 (used in the final prototype)	Excluded from cost breakdown as lower cost unit is more sus-

		Arduino Uno REV3 (used in the initial prototype)	tainable and equally as functional €28,85
		Breadboards, Cables	€10,23 (Set of 4 breadboards, 120 cables)
	Sensing	NFC Readers (PN532) NFC tags	€37,56 (Set of 6 readers, 12 tags)
	Output	Projector/Screen with integrated speakers Green LEDs LED holders	Projector: €35,99 LEDS (Set of 24) €6,38 LED holders (Set of 50): €5,78
	3D Printer	Bambu A1 mini	Excluded from Cost Breakdown
	Laser Cutter	Epilog Laser Fusion M2	Excluded from Cost Breakdown
Materials	3D Model	Copy of Caryatid C from MyMiniFactory	Free
	Filament	PLA Marble, SUNLU PLA+ (Black & White)	250g Marble PLA: €7.23 390g SUNLU PLA+ (Black & White): €8,61
	Magnets	4x2mm magnets	€9,46

			(Set of 100 magnets)
	Wood MDF	6 mm, 3x 500x800 panels	Roughly €27 (Cost taken from Chadwicks.ie)
	Fixings	Hot Glue Gun Hot Glue Gun Sticks Superglue Wood Glue	Hot Glue Gun: €9,99 Hot Glue Gun Sticks (Set of 30): €3,00 Superglue: €3,99 Wood Glue: €3,70
Software	3D Modelling Editing	Meshmixer Blender	Free
	Slicer Programming	BambuStudio Arduino IDE Processing	Free
	Vector Drawing	Affinity Vector	Free
Total Cost			**€197,77**

6 Discussion

6.1 Significance of Results

The findings of this research demonstrate that a 3D-printed Tangible Smart Replica (TSR) of an Ancient Greek statue can be designed to significantly enhance visitor engagement while remaining a viable, low-cost solution for long-term museum integration. By synthesising quantitative and qualitative data from user testing with qualitative insights from the expert interview, this study provides a robust answer to the central research question. It proves that physical interactivity, when supported by reliable open-source technology, serves as a powerful catalyst for both enjoyment and education.

6.1.1 Enhancing Engagement and Information Recall

The primary evidence of this study's significance lies in the successful validation of Hypotheses 1 and 2.

> *H1 (Engagement): Interactivity achieved through the assembly and placement of the smart replica significantly increases visitor enjoyment in a museum context compared to a traditional static display.*
>
> *H2 (Recall): Interactivity achieved through the assembly and placement of the smart replica, supported by an auditory and visual information display, significantly increases visitor recall in a museum context compared with a traditional static display.*

The interactive prototype achieved a mean enjoyment rating of 4.6 on a 5-point Likert scale, far exceeding the acceptance metric of 4.0 established in Chapter 3.5. This quantitative success was mirrored in participant feedback. For instance, Participant 14 noted, "I think it's very innovative and something that I would definitely walk towards straight away in a museum as opposed to just looking at something static. Because I'm not a massive museum person, but that would interest me." And Participant 02 said, "I adore museums with interaction pieces in it. […] I would […] visit more exhibits like that".

This element translated directly into cognitive gains, with the interactive group achieving a 34% higher score in the post-interaction knowledge quiz compared to the static group. This

improved score validates hypothesis 2 and suggests that the embodied cognition facilitated by the magnetic puzzle assembly acts as a cognitive hook, allowing visitors to internalise historical information more effectively than through passive observation.

> *"I feel like many people learn more or you- you get more of their attention, if you would use a different […]a different sense, like touch, sounds" (P06)*

> *"I think being able to kind of touch the figures and put them in different places would definitely get my brain going a bit better." (P07)*

This confirms that the third aim, which aimed to investigate the impact of tangible interaction on recall and enjoyment, was not only fulfilled but also serves as a compelling argument for the wider adoption of TSRs in heritage education. The full list of aims and objectives can be found in Chapter 1.2.

6.1.2 Technical Reliability and User Experience

Central to the second aim was the integration of a reliable, rewarding digital interface. The objective for the NFC-triggered system was to provide a logical reward within a two-second window. The prototype achieved a near-instantaneous response time (under 0.6 seconds), which was critical to maintaining the flow of the user experience (Objective 2). This technical seamlessness contributed to an exceptional System Usability Scale (SUS) score of 94.75. Achieving a score in the "A" category (above 80.3) is significant as it suggests that the complexity of the internal electronics, the Arduino microcontrollers and PN532 NFC readers did not create a barrier to entry. Instead, the technology remained "invisible," allowing users to focus on the narrative output. Participants frequently remarked on this, with Participant 02 stating that "I would say that was quite intuitive" and Participant 04 noting that "[the purpose of the prototype] was clear".

6.1.3 Practicality, Sustainability, and Safety

The research successfully addressed the complex balance between durability and cost-effectiveness, thereby validating Hypotheses 3 and 4.

> *H3 (Practicality): A 3D-printed replica constructed as a puzzle is practical for long-term integration in a museum environment.*

H4 (Sustainability): A 3D-printed replica constructed as a puzzle is sufficiently durable and sustainable for long-term integration and repeated use in a high-traffic museum environment.

While resin is often cited for its high durability, this study proved that PLA is the superior choice for sustainable museum integration due to its ease of maintenance and low replacement cost. Central to the first aim, the prototype's total material cost of €197,77 (excluding machinery) sits below the €200 threshold, fulfilling the criteria for a budget-friendly solution. Durability was physically validated through 113 successful assemblies (50 during development and 63 during user testing) and a 1.5-metre drop test, which demonstrated no structural failure or damage, thereby satisfying the objective of a robust design (Objective 1).

Furthermore, the interview with Maria Cagney provided the necessary professional validation that the prototype is theoretically and practically ready for a museum floor, provided that staff-centric longevity metrics are followed. By ensuring the system operates at a safe 5V current and prioritising post-processing techniques such as sanding to enhance user safety, the project met all its safety and ethical objectives. Additionally, no incidents occurred during the prototype's development or testing, indicating that the final replica is safe to handle (Objective 4).

6.1.4 Answering the Research Question

The central aim of this study was to determine how a 3D-printed Tangible Smart Replica (TSR) of an Ancient Greek statue should be designed to improve visitor engagement while remaining sustainable and practical for long-term museum integration. The evidence gathered suggests that the solution lies in a hybrid design approach that balances physical tactile engagement with a low-cost, modular technical infrastructure. By utilising the Caryatids of the Erechtheion as a case study, this research demonstrates that engagement is effectively improved when the replica is designed as a physical puzzle. The use of magnetic connectors facilitates a hands-on reconstruction process that triggers embodied learning, moving beyond the passive observation characteristic of traditional exhibits. This physical challenge provides a cognitive hook that ensures the educational content is more deeply internalised, as evidenced by the 34% increase in recall scores. Ultimately, the research concludes that a successful TSR must be narratively linked. The physical act of assembly must be met with immediate, multisensory feedback.

Sustainability and practicality are achieved by intentionally selecting accessible materials and open-source technology. The design prioritises the use of PLA and FDM printing over more expensive resins, not only to keep the fabrication costs below the €200 mark but to ensure that components can be easily replaced if damaged. By building the technological side of the replica on an Arduino-based system with PN532 NFC readers, the study proves that complex, high-engagement interactions do not require expensive, proprietary hardware. The Arduino system can be easily maintained by non-technical staff if an error occurs, due to its open-source documentation. This technical accessibility is crucial for long-term integration, as it empowers non-technical museum staff to maintain and repair the exhibit independently, addressing the common institutional barrier of a lack of on-site technologists. This was further validated by Maria Cagney when she was presented with the prototype. Additionally, the near-instantaneous audio-visual response to the correct placement of the Caryatid's components ensures that the technology remains a rewarding extension of the physical object rather than a distraction.

This study, therefore, provides a scalable blueprint for museums. By combining the durability of 3D-printed materials with the flexibility of open-source electronics and the psychological appeal of puzzle-based interaction, institutions can create deeply engaging exhibits that are financially and operationally sustainable.

6.2 Comparison with Existing Results

The findings from this study demonstrate a significant advancement in the application of 3D-printed Tangible Smart Replicas in museum contexts, directly addressing several key areas established in existing literature. Wilson et al. (2018b) previously argued that poor-quality prints significantly reduce visitor satisfaction. This research goes on to prove that high-quality digital fabrication can overcome this barrier of reduced visitor satisfaction. This was evidenced by Participant 20, who noted that the quality of the replica was noticeably superior to that seen in other institutions, thereby validating the success of the post-processing and material choices employed in this research. Furthermore, this study achieved a Grade A System Usability Scale (SUS) score of 94.75. This high score confirms that the interface developed here successfully offers the low-barrier entry point that Wacker et al. (2016) identified as essential for avoiding the "app fatigue" and "digital escapism" common in traditional digital museum guides.

The preference for ambient or “sound-in-place” audio over isolated experiences, such as headphones, a concept established by Petrelli et al. (2016), was strongly reinforced by participants' qualitative feedback. Participant 13 specifically highlighted how the “sound-in-place” approach fostered a sense of community and collective meaning-making.

> *“ I think that interaction element is nice because it would mean that if I was with someone else in a museum, that there'd be more […] listening together. I think there should be more of that if you're trying to like spend time with someone in the museum, if that makes sense. Because that's something I'd probably be more inclined to do if I was with other people […] I think it's more accessible to a bigger group of people which is nice. I like that” - P13*

This also aligns with Schou and Løvlie’s (2020) observation that tangible interactives naturally facilitate shared social interactions. Quantitatively, the interactive exhibit achieved an average dwell time of 269.6 seconds, a 156.3% increase over the static display. This mirrors the findings of Wilson et al. (2018b), where 93% of participants believed tactile replicas would enhance their experience. This is consistent with another finding of this study, where 18 out of 20 (90%) participants said they think that the interactive exhibit would improve their engagement in a museum. Additionally, the 34% improvement in information recall among the interactive group supports the "embodied cognition" theories of Liao and Noor (2023), who suggested that physical reconstruction serves as a powerful "cognitive hook" for deeper historical learning.

Finally, the study successfully integrated the design criteria proposed by Maria Cagney (2026) regarding the practicalities of museum maintenance and visitor safety. By prioritising thorough sanding and using a higher infill setting to ensure authenticity, the prototype avoided the "rough edges" and "broken immersion" that can plague low-cost PLA prints. This study also adhered to the “Do-It-With-Others” philosophy introduced by Petrelli et al. (2016) by consulting a museum curator during the design process and using standard, easily sourceable components. This approach directly addresses the concerns raised by Marshall et al. (2016) and McDermott et al. (2014) regarding the lack of internal technologists in museums, ensuring that the system is not a high-tech solution but a sustainable, repairable tool for long-term heritage education.

6.3 Research Implications

The findings of this study offer several significant implications for the field of museum technology, particularly by addressing gaps where previous research has remained fragmented. Existing literature tends to be divided into studies on technical feasibility, such as D'Agnano et al. (2025), and studies on visitor attitudes, as seen in Wilson et al. (2018b). However, there remains a lack of comprehensive assessment regarding the intersection of low-cost technical solutions and measurable visitor engagement. This research bridges that gap by providing an analysis of a budget-friendly, long-term solution utilising an Arduino and 3D printing. By doing so, it moves beyond mere interactivity to directly link the implementation of such systems with the practicalities of museum staff maintainability.

A significant contribution of this work is the exploration of staff-centric longevity metrics, a factor often overlooked in current evaluations of museum exhibits. Drawing on professional insights from an interview with Maria Cagney, this study offers an evaluation of prototype maintainability from a staff perspective and uses this perspective to define staff-centric longevity metrics. When asked what prevents museums from integrating interactive exhibits, Cagney most frequently cited access to technology and its documentation, alongside budget constraints.

This research report presents itself as a standardised, sustainable workflow which is critical to allow non-technical museum personnel to independently manage and update tangible systems without specialist knowledge. Additionally, because the prototype developed for this research relies on basic technology and open-source systems, it demonstrates a viable pathway for museums to move beyond the initial collaborative design phase and into independent, long-term operation.

Finally, this research advances the application of NFC technology within heritage contexts. While Marshall et al. (2016) validated the use of NFCs for content triggering, this study investigates a more nuanced application: the effectiveness of using multiple NFC localisation points to drive different narratives within a single 3D form. By doing so, it provides a foundation for more content-driven tangible interfaces.

6.4 Limitations and Future Research

While this study successfully demonstrates the viability of low-cost, interactive museum exhibits, several limitations emerged during the development and testing phases, providing ground for future investigation. The most immediate constraints were budget and resource availability, necessitating a pragmatic balance between project scope and execution. The physical scale of the exhibit was restricted, and certain aesthetic choices were bypassed in favour of available materials. For instance, the circular engravings on the lid were originally envisioned as laser-cut frosted acrylic with integrated LED rings to provide a more refined visual feedback system. Future iterations could explore higher-fidelity materials to enhance the installation's professional presence. However, budget constraints need to be considered to ensure the exhibit remains viable for smaller museums.

User testing further highlighted mechanical and technical points for improvement that were deemed out of scope for this prototype but remain critical for long-term museum deployment. Participants suggested that increasing the weight and thickness of the replicas, particularly delicate features such as the hands, would improve user confidence and prevent fear of breakage. This is supported by qualitative interview data, in which participants expressed a hesitant approach to the smaller components, suggesting that an even higher infill setting could be adopted in future iterations to enhance perceived authenticity without significantly inflating material costs.

Technically, more advanced programming and hardware are required to ensure the system triggers only once the statue is fully assembled, rather than triggering when only the feet component is present. By addressing these technical refinements, future research can improve both accessibility and operational longevity, alongside the integration of digital interfaces for multilingual support and hygiene stations.

The demographic profile of the testing group also presents a limitation, as the majority of participants were peers aged between 21 to 24. Although participants were encouraged to provide candid feedback, the lack of age diversity and the fact that testing occurred in a university setting rather than a live museum environment may influence the generalisability of the findings. Furthermore, while this study addressed component handling, future iterations should consider age-specific guidelines or supervision requirements for children under 13 to prevent damage from rough handling.

The limitations identified during this study establish a clear foundation for subsequent research and iterative development. Primarily, moving the prototype from a controlled university setting into a live museum environment. This would allow for a more authentic assessment of both visitor engagement across a broader demographic. Such a study would provide additional data to validate the system's long-term maintainability, since the longevity metrics in this paper are based mostly on a prototype evaluation conducted by Maria Cagney, a museum curator at the Hunt Museum. Lastly, a live museum environment would help determine whether the recorded increase in dwell time is sustained beyond the initial introduction of the interaction.

Finally, investigating the scalability of this model is also a priority. Research should examine whether the low-cost Tangible Smart Replica framework can be successfully adapted to larger, more intricate artefacts or to different categories of museum collections, such as natural history or industrial heritage.

7 Conclusion

This study has successfully demonstrated that a 3D-printed Tangible Smart Replica of an ancient Greek statue can significantly improve visitor engagement and information recall while remaining a sustainable and practical solution for museum integration. By fulfilling the primary research aims, this project has established that physical interactivity, specifically through the assembly of a magnetic puzzle, serves as a powerful cognitive hook enabling visitors to internalise historical information more effectively than through traditional passive observation. The interactive prototype far exceeded acceptance metrics for enjoyment, achieving a mean rating of 4.6 on a 5-point scale, and proved more effective at facilitating knowledge retention than static displays by improving information retention by 34%.

The system's technical reliability was also validated, demonstrating that low-cost, open-source technologies such as an Arduino and NFC technology can support sophisticated, high-engagement interactions without the need for expensive, proprietary hardware. This approach ensures that the exhibit is not only affordable, with fabrication costs kept below €200, but also maintainable by non-technical museum staff who can replace and repair 3D-printed components as validated by Maria Cagney. Such findings address the critical institutional barrier of limited technical support and budgets in the heritage sector.

Despite these successes, several limitations were identified, providing a clear foundation for future development. The physical scale and aesthetic choices were constrained by budget and resource availability, leading to the use of accessible PLA rather than resin materials or more refined visual feedback systems, such as integrated LED rings. Furthermore, user testing in a controlled university setting with a limited demographic may not fully reflect the challenges of a live museum environment. Future iterations of the prototype present an opportunity to further advance the programming and hardware to ensure the audio only triggers upon full puzzle completion, rather than triggering upon placing only the feet piece.

Future research should focus on longitudinal studies in live museum settings to gather further data on the long-term durability of 3D-printed components under high-traffic conditions and to determine whether engagement levels are sustained beyond the initial novelty. There is potential to expand the system's inclusivity by incorporating digital interfaces that support multiple languages and hygiene stations. Ultimately, the Tangible Smart Replica represents a

vital shift from passive observation toward active, embodied discovery, providing a scalable blueprint that is not merely a technical novelty but a robust and essential tool for the future of sustainable, hands-on heritage education.

8 Appendix

8.1 External Files

Access to "Copy of Caryatid C, Erechtheion of the Acropolis" from SMK - Statens Museum for Kunst: https://www.myminifactory.com/object/3d-print-copy-of-caryatid-c-erechtheion-of-the-acropolis-100240

Access to the code library for writing to an NFC tag: https://github.com/adafruit/Adafruit-PN532

Access to the SparkFun tutorial "Connecting Arduino to Processing": https://learn.sparkfun.com/tutorials/connecting-arduino-to-processing/all

Access to the 3D Model of the Caryatids used for the visual output: https://sketchfab.com/3d-models/athens-acropolis-museum-caryatids-1f15bbc45c2046859396d321a6ec918f

Access to the Blender Scene used for the visual output: https://www.blenderkit.com/asset-gallery-detail/86d96500-fce9-4cb5-a73d-c15060a332c4/

Access to the Plant used in the visual output: https://www.blenderkit.com/asset-gallery-detail/7185ec5c-a1d0-419d-a0c6-844d8bb652c7/?query=category_subtree:model+banana+plant+order:_score

Access to the Ceiling Lights used in the visual output: https://www.blenderkit.com/asset-gallery-detail/30fe85e3-f489-4420-8867-2755ab699158/?query=category_subtree:ceiling-light

Access to Arduino UNO R3 Screwless Enclosure: https://makerworld.com/en/models/169717-arduino-uno-r3-screwless-enclosure?from=search#profileId-186362

Access to the Elechouse PN532 V3 Datasheet: https://www.elechouse.com/elechouse/images/product/PN532_module_V3/PN532_%20Manual_V3.pdf

Access to the “Gentle ding for saved settings confirmation” used in the video output: https://elevenlabs.io/sound-effects/success

Access to “Sign Stand (2 Versions)” by Mr.Cheez541: https://makerworld.com/en/models/604160-sign-stand-2-versions#profileId-1479617

Access to the UK Art’s Council’s Researcher’s Question Bank: https://www.artscouncil.org.uk/sites/default/files/S3D3_Researchers_Question_Bank.doc

8.2 Script for Auditory Output

Clip 1: Introduction

Welcome to the Erechtheion, the sacred temple on the Acropolis. Standing before you are the daughters of Athens, the Caryatids. These female marble figures have served as pillars supporting the temple’s southern porch for over 2,400 years. They are a unique and celebrated feature that has inspired countless imitations in later architecture.

Clip 2: The Name

Many statues of young women were called "Korai", meaning "daughters" or "maidens" in Greek. Today, these statues are known as Caryatids. The name 'Caryatid' refers to the 'Maiden of Caryae,' an ancient town near Sparta. To this day, they remain icons of Greek architecture.

Clip 3: The Punishment Theory

A theory by the Roman architect Vitruvius suggests these statues represent the women of Caryae, who were punished with hard labour for siding with the Persians during the second Persian invasion of Greece. In this view, their eternal stance captures the burden of a city’s past. However, this theory was later disputed.

Clip 4: Architectural Design

To support the heavy roof, sculptors carved thick folds of drapery to mimic the vertical grooves of a column. This clever design conceals their structural role, making the massive stone weight appear to rest lightly upon their heads.

Clip 5: Lifelike Pose

The sisters stand in a 'contrapposto' pose, with one leg straight and the other slightly bent, creating a sense of lifelike movement. With their flowing veils and elaborate braided hair, they appear not as static columns, but as living participants in a sacred procession.

Clip 6: The Missing Sister

Today, only five original sisters remain in Athens. In 1801, Lord Elgin removed one Caryatid, which now resides in the British Museum. In the Acropolis Museum in Athens, an empty space is kept open, symbolising the hope that the sisters will one day be reunited.

8.3 Code Library

8.3.1 Arduino IDE

```
#include <SPI.h>
#include <PN532_SPI.h>
#include "PN532.h"

// Define CS Pins (NFCs)
int csPins[] = {5, 6, 7, 2, 3, 4};
const int numReaders = 6;

// Hardware setup, Initialises all NFC readers
PN532_SPI pn532spi[] = {
  PN532_SPI(SPI, csPins[0]), PN532_SPI(SPI, csPins[1]),
  PN532_SPI(SPI, csPins[2]), PN532_SPI(SPI, csPins[3]),
  PN532_SPI(SPI, csPins[4]), PN532_SPI(SPI, csPins[5])
};

//Assigns LED pins
PN532* readers[numReaders];
int pins[numReaders] = {A0, A1, A2, A3, A4, A5};

// State Tracking, Sets up variables for later
bool tagDetected[numReaders]  = { false };
bool readerOK[numReaders]     = { false };
bool readerWarned[numReaders] = { false };
bool lockedOut[numReaders] = { false };
int missCount[numReaders]     = { 0 };
int activeReader              = -1;

// Tuning parameters, sets timings
const uint16_t TIMEOUT_TRACKING   = 50;   // ms — fast re-
confirm of known tag
const uint16_t TIMEOUT_SEARCHING  = 100;  // ms — thorough
search for new tag
const uint8_t  RF_WAKE_MS         = 10;   // ms — delay after
RF on
const uint8_t  READER_BREATHE_MS  = 5;    // ms — settle time
between readers
const int      MISS_THRESHOLD     = 5;    // misses before
confirming removal
const uint32_t HEALTH_CHECK_MS    = 5000; // ms — how often to
check reader health
const int      MAX_REINIT_TRIES   = 3;    // attempts before
giving up a reinit cycle

unsigned long lastHealthCheck = 0;

// Sets up NFC readers
bool initReader(int i) {
  readers[i]->begin();
  uint32_t versiondata = readers[i]->getFirmwareVersion();
  if (!versiondata) return false;
  readers[i]->setPassiveActivationRetries(0x05);
  readers[i]->SAMConfig();
  readers[i]->setRFField(0x00, 0x00);
  return true;
}

// Sets pin modes, turns LEDS off and NFC readers on, tests
all NFC readers
void setup(void) {
  Serial.begin(115200);

  for (int i = 0; i < numReaders; i++) {
    readers[i] = new PN532(pn532spi[i]);
    pinMode(csPins[i], OUTPUT);
    digitalWrite(csPins[i], HIGH);
    pinMode(pins[i], OUTPUT);
    digitalWrite(pins[i], LOW);
  }

  delay(200);
  for (int i = 0; i < numReaders; i++) {
    readerOK[i] = initReader(i);
    if (readerOK[i]) {
      Serial.print("Reader "); Serial.print(i + 1);
Serial.println(" is OK.");
    } else {
      Serial.print("Reader "); Serial.print(i + 1);
Serial.println(" failed!");
    }
  }
}

// Defines Health Check, initiates if NFC reader fails and
tries to restart reader
bool tryReinit(int i) {

  if (activeReader == i) {
    digitalWrite(pins[i], LOW);
    Serial.print("STOP_"); Serial.println(i + 1);
    tagDetected[i] = false;
    missCount[i]   = 0;
    lockedOut[i]   = false;
    activeReader   = -1;
  }

  readers[i]->setRFField(0x00, 0x00);
  delay(50);

  for (int attempt = 0; attempt < MAX_REINIT_TRIES; attempt++)
{
    if (initReader(i)) {
      Serial.print("Reader "); Serial.print(i + 1);
Serial.println(" recovered.");
      readerWarned[i] = false;
      return true;
    }
    delay(100);
  }

  return false;
}

// Runs Health Check
void runHealthChecks() {
  for (int i = 0; i < numReaders; i++) {
    if (i == activeReader) continue;

    if (!readerOK[i]) {
      // Always retry dead readers
      readerOK[i] = tryReinit(i);
    } else {
      // Ping healthy readers to catch newly stuck ones
      uint32_t versiondata = readers[i]->getFirmwareVersion();
      if (!versiondata) {
        Serial.print("Reader "); Serial.print(i + 1);
Serial.println(" not responding.");
        readerOK[i] = tryReinit(i);
      }
    }
  }
}
```

Writing to a Tag

```
#include <SPI.h>
#include <Adafruit_PN532.h>

#define PN532_SS 5

Adafruit_PN532 nfc(PN532_SS);

void setup() {
  Serial.begin(115200);
  nfc.begin();

  if (!nfc.getFirmwareVersion()) {
    Serial.println("PN532 not found");
    while (1);
  }

  nfc.setPassiveActivationRetries(0xFF);
  nfc.SAMConfig();
  Serial.println("Place your MIFARE Classic tag on the
reader...");
}

void loop() {
  uint8_t uid[7]    = {0};
  uint8_t uidLength = 0;

  if (!nfc.readPassiveTargetID(PN532_MIFARE_ISO14443A, uid,
&uidLength)) return;

  Serial.println("Tag found! Writing NDEF URI...");

  if (nfc.mifareclassic_WriteNDEFURI(1, 1, "arduino.cc")) {
    Serial.println("Done! http://www.arduino.cc written
successfully.");
  } else {
    Serial.println("Write failed. Tag must be a blank MIFARE
Classic 1K.");
  }

  while (1);
}
```

8.3.2 Processing

```
import processing.video.*;
import processing.serial.*;
import processing.sound.*;

Serial myPort;
SoundFile pingSound;
Movie[] mainClips = new Movie[6];  // Primary loops clips, one
per tag
Movie[] endClips = new Movie[6];   // Closes playing clips
when a tag is removed early
Movie currentMovie;                // The clip currently on
screen
Movie nextMovie;                   // Queuing clip waiting to
swap in during transition
PImage idleImage;                  // Shown on first arrival
and after idle timeout
PImage instructionsImage;          // Shown between
interactions once a tag has been scanned

// IDLE STATE TRACKING
// After 30 seconds with no interaction, the display reverts
to the idle image
boolean hasHadInteraction = false;
long lastInteractionTime  = 0;
final long IDLE_RESET_MS  = 30000; // 30 seconds

int activeIndex = 0;               // Index (0–5) of the
currently active tag/clip
boolean isMainPlaying = false;    // True while a main clip is
playing (false during end clips)
boolean isTransitioning = false; // True for one frame while
swapping currentMovie to nextMovie
boolean videoFullyComplete = false; // True once a main clip
has played all the way through

// STALL DETECTION
// If the playhead stops advancing past the halfway point, we
treat it as a finished video
float lastMovieTime = 0;
int stalledFrames = 0;
final int STALL_THRESHOLD = 30; // Frames of no progress
before we consider the video done


void setup() {
  fullScreen(P2D);

  // LOAD STATIC IMAGES
  idleImage = loadImage("idle.png");
  instructionsImage = loadImage("instructions.png");

  // LOAD AUDIO
  try {
    pingSound = new SoundFile(this, "ping.mp3");
    println("ping.mp3 loaded.");
  } catch (Exception e) {
    println("!!! Error loading ping.mp3: " + e.getMessage());
  }

  // CONFIRM IMAGES LOADED
  if (idleImage != null) println("idle.png loaded.");
  else println("!!! Error: idle.png not found.");
  if (instructionsImage != null) println("instructions.png
loaded.");
  else println("!!! Error: instructions.png not found.");

  // SETUP SERIAL PORT
  // Attempts to connect on the third available port at 115200
baud
  try {
    if (Serial.list().length > 2) {
      String portName = Serial.list()[2];
      myPort = new Serial(this, portName, 115200);
      println("Serial connected to: " + portName);
    } else {
      println("Serial Port Error: Index 2 not available.
Available ports: " + Serial.list().length);
    }
  } catch (Exception e) {
    println("Serial Port Error: " + e.getMessage());
  }

  // LOAD VIDEO CLIPS
  // Each tag (1–6) has a main clip and an end clip
  println("Loading videos...");
  for (int i = 0; i < 6; i++) {
    int id = i + 1;
    mainClips[i] = new Movie(this, "Clip_" + id + ".mp4");
    endClips[i]  = new Movie(this, "Clip_" + id + "_end.mp4");
  }

  isMainPlaying = false;
  println("System Ready.");
}


void draw() {
  background(0);

  // READ INCOMING SERIAL COMMANDS
  // Drains all available bytes and dispatches each newline-
terminated command
  if (myPort != null) {
    while (myPort.available() > 0) {
      String inString = myPort.readStringUntil('\n');
      if (inString != null) processCommand(trim(inString));
    }
  }

  // IDLE TIMEOUT CHECK
  // If no video is playing and the interaction timer has
expired, revert to idle image
  if (hasHadInteraction && currentMovie == null) {
    if (millis() - lastInteractionTime >= IDLE_RESET_MS) {
      hasHadInteraction = false;
      println("Idle timeout. Returning to idle.png.");
    }
  }

  // APPLY PENDING TRANSITION
  // Swaps in the queued next clip on the frame after it was
requested,
  // giving the new movie time to start before the old one is
stopped
  if (isTransitioning) {
    if (currentMovie != null) currentMovie.stop();
    currentMovie = nextMovie;
    nextMovie = null;
    isTransitioning = false;
  }

  // RENDER CURRENT FRAME
  // Priority: playing video > instructions image > idle image
  if (currentMovie != null) {
    drawCentered(currentMovie);
  } else if (hasHadInteraction && instructionsImage != null) {
    drawCentered(instructionsImage);
  } else if (idleImage != null) {
    drawCentered(idleImage);
  }

  // CHECK WHETHER THE CURRENT VIDEO HAS ENDED
  checkVideoEnd();
}


// DRAW CENTERED — letterbox/pillarbox an image or video frame
to fill the screen
void drawCentered(PImage img) {
  float aspect = (float)img.width / img.height;
  float targetW = width;
  float targetH = width / aspect;

  // If the width-fitted height exceeds the screen, fit by
height instead
  if (targetH > height) {
    targetH = height;
    targetW = height * aspect;
  }

  float x = (width - targetW) / 2;
  float y = (height - targetH) / 2;

  image(img, x, y, targetW, targetH);
}
```

```
// CHECK VIDEO END
// Detects when the current clip has finished, either by
reaching its duration
// or by stalling (playhead stops advancing past the halfway
point)
void checkVideoEnd() {
  if (currentMovie != null) {
    float dur = currentMovie.duration();
    float t   = currentMovie.time();

    if (dur <= 0) return;

    // STALL DETECTION — increment counter if time has frozen
past the midpoint
    if (t == lastMovieTime && t > dur * 0.5) {
      stalledFrames++;
    } else {
      stalledFrames = 0;
    }
    lastMovieTime = t;

    boolean ended = (t >= dur - 0.2) || (t >= dur * 0.98) ||
(stalledFrames >= STALL_THRESHOLD);

    // MAIN CLIP ENDED — notify Arduino to turn off the LED,
then clear the screen
    if (isMainPlaying && ended) {
      println("Main clip finished.");
      stalledFrames = 0;
      if (myPort != null) myPort.write("LED_OFF_" +
(activeIndex + 1) + "\n");
      currentMovie.stop();
      currentMovie = null;
      isMainPlaying = false;
      videoFullyComplete = true;
      lastInteractionTime = millis();

    // END CLIP ENDED — simply clear the screen and reset the
idle timer
    } else if (!isMainPlaying && ended) {
      println("End clip finished.");
      stalledFrames = 0;
      currentMovie.stop();
      currentMovie = null;
      lastInteractionTime = millis();
    }
  }
}
```

```
// PROCESS SERIAL COMMAND
// Handles START_{id} (tag placed) and STOP_{id} (tag removed)
messages from Arduino
void processCommand(String cmd) {
  println("Received: " + cmd);

  // TAG PLACED — start the main clip for this tag and play
the ping sound
  if (cmd.startsWith("START_")) {
    int id = int(cmd.substring(6));
    int index = id - 1;
    if (index >= 0 && index < 6) {
      activeIndex = index;
      videoFullyComplete = false;
      hasHadInteraction = true;
      lastInteractionTime = millis();
      triggerSwitchTo(mainClips[index], true);

      if (pingSound != null) {
        pingSound.play();
      }
    }
  }
  // TAG REMOVED EARLY — switch to the end clip if the main
clip hasn't finished yet
  else if (cmd.startsWith("STOP_")) {
    int id = int(cmd.substring(5));
    int index = id - 1;
    if (index == activeIndex && isMainPlaying &&
!videoFullyComplete) {
      lastInteractionTime = millis();
      triggerSwitchTo(endClips[index], false);
    }
  }
}


// TRIGGER SWITCH TO — queue a clip to become the next
currentMovie
// Rewinds and starts the target clip, then sets the
transition flag
// so draw() performs the actual swap on the next frame
void triggerSwitchTo(Movie target, boolean isMain) {
  if (target == null) {
    println("Error: Target movie clip is null!");
    return;
  }
  nextMovie = target;
  nextMovie.jump(0);
  nextMovie.play();

  isTransitioning = true;
  isMainPlaying = isMain;
}


// MOVIE EVENT — called by Processing each time a new video
frame is available
void movieEvent(Movie m) {
  m.read();
}
```

8.4 Survey Questions

Question 1: What is the name of the ancient structure where the original Caryatid statues are located?

Answer: The Erechtheion

Question 2: Which function did the original Caryatids serve?

Answer: A structural support column

Question 3: The Caryatids were carved in a distinct pose, placing their weight mostly on one straight leg while the other is slightly bent. This posture is known as…

Answer: Contrapposto

Question 4: What material were the original Caryatids primarily made of?

Answer: Marble

Question 5: What design feature of the statues was explicitly intended to conceal their structural role as columns?

Answer: The folds of the fabric/drapery

Question 6: According to one historical theory, what punishment were the women of Caryae condemned to, which the statues were meant to represent?

Answer: Hard labour

Question 7: Before the name "Caryatids" became widely used, the figures were often called "Korai". What does "Korai" mean in Greek?

Answer: Daughters or Maidens

Question 8: True or False: The original Caryatids remain standing on the Erechtheion today.

Answer: False

8.5 Survey Answers

TABLE 17: PARTICIPANT RESULTS

Participant	Testing Group	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
01	Group B	The Erechtheion	A structural support column	Contrapposto	Marble	The folds of the fabric/ drapery	Hard labour	Daughters or maidens	False
02	Group B	The Erechtheion	A structural support column	Contrapposto	Marble	The bent left leg	Hard labour	Daughters	False
03	Group B	The Parthenon	A structural support column	Contrapposto	Terracotta	The folds of the fabric/ drapery	Siding with the Persians	Daughters	True
04	Group B	The Erechtheion	A structural support column	Contrapposto	Marble	The folds of the fabric/ drapery	Hard labour	Name of a town?	True
05	Group B	The Erechtheion	A structural support column	Contrapposto	Marble	The folds of the fabric/ drapery	Hard labour	Daughters or maidens	False

06	Group B	The Erech-theion	A structural support col-umn	Contrap-posto	Mar-ble	The folds of the fabric/ drapery	Hard labour	I don't remem-ber	True
07	Group B	The Erech-theion	A structural support col-umn	Metope	Mar-ble	The folds of the fabric/ drapery	Siding with the Per-sians	Maiden	False
08	Group B	The Erech-theion	A structural support col-umn	Contrap-posto	Mar-ble	The folds of the fabric/ drapery	Hard labour	Maidens	True
09	Group B	The Parthenon	A structural support col-umn	Contrap-posto	Mar-ble	The bent left leg	They went against Per-sia	Sisters	False
10	Group B	The Erech-theion	A structural support col-umn	Contrap-posto	Mar-ble	The folds of the fabric/ drapery	Hard labour	Sisters	False
11	Group A	The Erech-theion	A structural support col-umn	Contrap-posto	Lime-stone	The column capital on the head	I forgot	Daugh-ters	True
12	Group A	The Erech-theion	A structural support col-umn	Entasis	Mar-ble	The column capital on the head	Unsure	Unsure	False
13	Group A	The Erech-theion	A religious idol	Contrap-posto	Mar-ble	The column capital on the head	Forced to stand serve as pillars	Maidens, Young women	False
14	Group A	The Erech-theion	A structural support col-umn	Contrap-posto	Mar-ble	The folds of the fabric/ drapery	I don't know	I don't know	False
15	Group A	The Erech-theion	A structural support col-umn	Entasis	Mar-ble	The folds of the fabric/ drapery	Hard labour	Daugh-ters	True
16	Group A	The Parthenon	A structural support col-umn	Metope	Ter-ra-cotta	The column capital on the head	I don't know	No idea	True
17	Group A	The Parthenon	A structural support col-umn	Contrap-posto	Mar-ble	The folds of the fabric/ drapery	I don't know	Daugh-ters	False
18	Group A	The Erech-theion	A structural support col-umn	Contrap-posto	Ter-ra-cotta	The folds of the fabric/ drapery	To leave Greece	I don't know	False
19	Group A	The Parthenon	A burial marker	Contrap-posto	Ter-ra-cotta	The bent left leg	I don't know	Daugh-ters	False

20	Group A	The Erech-theion	A structural support col-umn	Contrap-posto	Mar-ble	The folds of the fabric/ drapery	Symbolising the city's burden	Maid	False

8.6 System-Usability-Scale Questions

1. I think that I would like to use this system frequently.
2. I found the system to be more complicated than it needed to be.
3. I thought the system was easy to use.
4. I think I would need help from a tech expert to use this system.
5. Everything in the system seemed to work well together.
6. The system felt inconsistent in how things worked.
7. I think most people could learn to use this system quickly.
8. Using the system felt like a hassle.
9. I felt confident while using the system.
10. I had to learn a lot before I could start using the system properly.

8.7 Interview Questions

Introduction

Hello, my name is Annika Jungfleisch, and I am currently undertaking a Final Year Project at the University of Limerick under Dr Mark Marshall. My research, "From Artefact to Interaction: Tangible Smart Replica of an Ancient Greek Statue," aims to design a 3D-printed interactive replica to enhance visitor engagement while being sustainable and suitable for museum integration.

The purpose of this interview is to gather insights on the prototype's enjoyment and usability. There are no risks, and your personal information or any identifying information will not be

included in the report. Your participation is voluntary, and you have the right to withdraw at any time. Thank you for taking part in this research project.

Part I: Engagement and Enjoyment

1. To start, what is your general impression of the exhibit you were presented with today?
2. On a scale of 1–5 (5 = Excellent), how would you rate your enjoyment of this exhibit? Why?
3. How engaging or interesting did you find the learning experience about the statue's history?
4. Did you learn something you didn't previously know about Ancient Greece?

Group B only:

(1) Did the puzzle interaction feel like a meaningful way to learn, or was it a distraction from the information? Why?
(2) Compared to reading a standard museum plaque, did this feel like a more effective/engaging way to learn?
(3) What was the most interesting thing you looked at/ did/ read/ listened to?

2. Does this experience make you more likely to visit an exhibit that is structured in a similar manner?

Group A only:

(1) If you were presented with an interactive museum experience that allowed you to touch replicas of the statues and offered different information outputs, such as videos and audio, in addition to text, would you have enjoyed the exhibit more?
(2) Do you think you would have learned more, or would you be able to recall the information better?

Part II: Usability and Experience (GROUP B ONLY)

3. Was the purpose of the replica clear before you started?
4. On a scale of 1–5 (5 = Very Easy), how intuitive was the statue assembly? Did the "game" aspect help you focus on the history, or did it feel like a distraction?

5. On a scale of 1–5 (5 = Excellent), how did the material and the weight of the statue feel to you?
6. Did the visual and auditory feedback you received feel immediate and logical after placing the assembled puzzle?
7. Was there anything about the physical interaction that was confusing or felt like it could break?
8. Do you think this type of exhibit would be suitable for all ages in a museum? Why?
9. Do you have any suggestions for improving the way the information and the replica were presented? Is there anything you would do differently next time?

Finishing up

Thank you for taking part in this interview. Do you have anything further to add, or has the interview brought anything up you'd like to address at this point? If you have any additional thoughts or would like to provide any further information after our conversation, please feel free to reach out. Once again, thank you for your participation.

8.8 User Testing Transcripts

[...] = Break

- = interrupted sentence

[text] = clarifications on what the participant talked about

8.8.1 Participant 01

Annika 0:00

Thank you for taking part in this interview. The purpose of the interview is to gather insights on the prototypes' enjoyment and usability. Your participation is voluntary, and you have the right to withdraw at any time. To start with, what is your general impression of the prototype you were presented with today?

Participant 01 0:25

I really liked it. I thought it was really cool. I didn't know a lot about [...] this history, like the actual bits of it, and so it's really cool to see about the history. And I really enjoyed, actually tactile building a puzzle, because I enjoyed, like, hearing [...] about it, and then being able to see the bits of like the bent leg. So overall, that was really cool.

Annika 0:53

Okay, and then on a scale of one to five, with five being excellent, how would you rate your enjoyment of this overall exhibit, and why?

Participant 01 1:03

I would say five. I felt like it did everything an exhibit should. I felt like I had- [...] enjoyed myself. I learned something at the same time. I felt like I was engaged while I was learning. It didn't feel like a chore in order like to learn these facts, but I felt like I enjoyed the aspect of learning.

Annika 1:23

Almost like a game?

Participant 01 1:24

Yeah, I think so. It felt like ehm [...] it was almost like accidental learning, like it snuck in.

Annika 1:34

Did the puzzle interaction feel like a meaningful way to learn, or was it a distraction from the information?

Participant 01 1:42

I thought it was meaningful, ehm, I liked how it kind of abstracted the different parts of it, eh, as I feel oftentimes, when you're at an art museum, you kind of see- you just see like the Mona Lisa, for example. You don't really appreciate like the brushstrokes or like the intent behind art. I enjoyed being able to see each part of it [the statue] and how it came together, because, like, the people who carved this [the statue] spent probably a lot of time on just like each individual foot [of the statue], and it's nice to be able to see that and how it all fits together.

Annika 2:17

And then you mentioned this before, but how did you feel about having multiple ways of receiving the information, so being able to read it, but also listen to it?

Participant 01 2:29

I really enjoy it. I feel I sometimes read better when I hear it at the same time, because oftentimes when I read I like, skip sentences and when I hear it, especially for, like, difficult words, like, I don't know if I can still pronounce it, but the Contrapposto pose, I enjoy being able to hear it, “Oh, that's how that's actually pronounced.” So I enjoy, like, the many things at the same time.

Annika 2:58

How engaging or interesting did you find the learning experience about the statue's history?

Participant 01 3:03

It was very engaging, eh, because I found myself also while hearing it, I found myself reading different bits, I'd even- I went back to one bit because I wanted to hear more about, like, the bent leg, I was able to, like, easily go back to the bit I wanted to.

Annika 3:25

Compared to reading a standard museum plaque, so an information sign, did this feel like a more effective, engaging way to learn, or not?

Participant 01 3:38

I think so. I've, like, I have a pretty good attention span, but I've even found myself starting to read like a piece of long text in front of something, getting bored halfway, and then walking off to the next thing. And so I liked how there was like something to keep me engaged while I learned. I'm very much a “keep my fingers busy” kind of person. So I felt like I was able to stay there and learn a lot better.

Annika 4:03

Did you learn something new that you didn't previously know about Ancient Greece?

Participant 01 4:08

I did. I think my favourite fact was kind of like, how they were kind of designed to- [...] as, like a reminder of the punishments and that kind of shows like the type of society they were living in as well that so much of the architecture was kind of built around this, and it kind of gives you an insight into what everyday life was like if they were shown these type of reminders.

Annika 4:45

What was the most interesting thing you looked at, did, read or listened to?

Participant 01 4:51

I think the most interesting was the actual assembly. I lik- I really liked the technology of it. Ehm, yeah, I was really intrigued by how it works. And I liked, yeah, how seamless it all felt. I don't even like- I can see one cable, but I liked how it just plays, and it just worked. I thought that was really cool.

Annika 5:17

As a note, that was the cable that connects the Arduino to my computer. Does this experience make you more likely to visit an exhibit about Ancient Greece?

Participant 01 5:28

I think definitely, I really liked, like, I don't know if it's the art style for statues, but I like how it was designed. I like how there's thought behind the architecture, and it seems to have a lot of meaning. I think that would be found in, like, other aspects of ancient Greek architecture as well.

Annika 5:48

Now we move on to the usability and experience part. Was the purpose of the replica clear before you started?

Participant 01 5:57

Yeah. Like, just by looking at it, I can kind of say, "Oh, this is going to be a puzzle." Like, it didn't look as if, "Oh, this thing's just broken." It looked like, very meaningfully in pieces. The mag-

nets were, like, nice to see. And it kind of gave you, like, an idea of how things would, like, fit together. And, yeah, the idea of it being a puzzle, and it kind of tells all like an idea in my head of how it would look before I even started.

Annika 6:22

On a scale of one to five, with five being very easy, how intuitive was the statue to assemble?

Participant 01 6:31

I would say five. I was able to do it like first try, without, ehm, like getting something in the wrong place, or having to redo it all. So yeah, I found it very easy.

Annika 6:42

Did the game aspect help you focus on the history, or did it feel like a distraction?

Participant 01 6:47

I think it helped me focus. Ehm [...] as I said before, I liked hearing about something, being able to actually feel it myself, and then even like reading different bits at the same time. So I liked that aspect of it.

Annika 7:04

On a scale of one to five, with five being excellent, how did the material and the weight of the statue feel to you?

Participant 01 7:12

I thought it was very good. Each of them feels like very heavy and premium, because sometimes you kind of feel some stuff, and it feels like it's gonna like-, like, even if you're allowed to touch it, it feels like you might even break in your hands. But this felt like very premium. Nothing felt like it would break, and I felt like I could manipulate it, like I would want to, without fear of actually causing damage. And it felt hefty, like an actual statue would.

Annika 7:45

Did the visual and auditory feedback you received feel immediate and logical after placing the assembled puzzle on the base?

Participant 01 7:52

Yes, there was like a little green light that lit up when that bit was done. And then, like the video, like there's like a spotlight that would have come and like it was cool to see like that when I put it here, it would show but there, I mean, let's say, "Start Here", for example, in that circle, it would go on the video to take the exact same place. And I felt like my actions in the real world were represented by the screen. And on the actual artefact.

Annika 8:22

Was there anything about the physical interaction that was confusing or felt like it could break?

Participant 01 8:27

No, ehm, my main interaction was with, eh, the statue, and I felt like I could, like, reassemble it over and over again. Like, I liked to take one bit out and have it all stay together. Even when I took one bite out, it didn't just come crumbling apart. So I thought it was very well built.

Annika 8:48

Do you think that this type of exhibit would be suitable for all ages in a museum?

Participant 01 8:54

Yes, I think for, like, children, it's the choking parts. I don't see any of those. And then for like adults, sometimes, ehm, the actual like gamification aspect of museum like making it too simple for them, or they might just not find it interesting, because, like, it's like, “Oh, can you colour in the picture of the dog?” Like that might not be interesting for an adult. I thought this struck a nice balance, I could see my niece being able to do this, well, also, I found it interesting as a 22-year-old.

Annika 9:24

How old is your niece?

Participant 01 9:27

She is 10. And four. I have a second niece.

Annika 9:32

Do you have any suggestions for improving the way the information and the replica were presented?

Participant 01 9:39

Um, I don't think so. Ehm, it took me a second, ehm, when I realised, like, there wasn't, like, a one set path [regarding the video clips]. I knew I had to start in one section, and it was clear, like, based on the words "Start Here" and even the text saying "Welcome". I thought for like a second there might be like, “Oh, this path,” but then I found it- kind of choose which bit you want to find out about next, and then you can chop and change and go back and like that kind of free-flowing aspect of it.

Annika 10:15

Like creating your own narrative?

Participant 01 10:17

Yes, it felt like I had control of it rather than- I was listening to a video just letting it wash over me.

Annika 10:25

More of an active experience than a passive one?

Participant 01 10:28

Yes, almost as if I was turning the pages more than- [...]

Annika 10:32

Is there anything you would do differently next time?

Participant 01 10:37

I don't think so, ehm. I believe I assembled it correctly. I was able to go through all six, ehm, spots. I was able to listen to it all. I didn't feel like I missed any information. So, no, I think I did it all how I would do it again.

Annika 10:56

Thank you so much for sharing your thoughts today. This is the end of the interview. Do you have anything further you want to add to this interview?

Participant 01 11:06

No, I just want to say again how cool I thought it was. I think it's really good. And I can kind of see, like, how there's more like applications of this outside of just like Greek statues. And I like, like, I can kind of see how, like, you could use this puzzle piece for other stuff as well. Even like a vase. I feel like that'd be nice to- fun to put a puzzle together of, yeah.

Annika 11:31

Okay, thank you so much.

8.8.2 Participant 02

Annika 0:00

Hello, thank you for taking the time to do my interview. The purpose of this interview is to gather insights on the prototypes' enjoyment, and usability. Your participation is voluntary, and you have the right to withdraw at any time. Thank you for taking part in this. So to start with, what is your general impression of the prototype you were presented with today?

Participant 02 0:26

The general impression, ehm, is quite fascinating. Ehm, I really liked that it was three sources of pursuing the information used, because I'm a terrible audio learner, and if it was only, eh, talking by audio, I would not remember like the biggest half of the information. So the text support really helped me, but also it's hard for me to focus on the text for a long time. So the audio sometimes helps me focus and supported the idea as well, that I actually was able, ehm, to remember the information, and also the visual representation was really amazing, because now, now I know that even if I forget the information, I will still remember how it looked like,

and after that was, eh, visual conception, I will remember the basis of information when it's needed, when I see it again.

Annika 1:37

On a scale of one to five, with five being excellent, how would you rate your enjoyment of this exhibit, and why?

Participant 02 1:44

One second. Let me think. […] I would say five. But the only, ehm, my only concern would be that there would be a lot, a lot of terms I haven't seen before, and when I first put it on some text, it started with dates, and my brain was automatically like, “Oh, that is too hard.” Or like, it’s like trying to shut off the information right away. But then, because of the different sorts of information coming in, I was still able to focus on the words like I would not recall- I would visually recall, because I have photo generic memory, I would visually recall what date was like, what numbers were there. But the main point that I really enjoyed was that even though there were unknown words for me, I did remember them afterwards.

Annika 2:54

Would it have helped you if there had been an option previously to have the audio in a different language?

Participant 02 3:05

Might be, but, yeah, well might be, but audio, for sure. The text- how would you change the text? That would be a different main point, because if it's an English text and a different language, audio will come in, I may be lost for a second, but I would, I don't know, in this case, whatever I would be focused on more.

Annika 3:27

And if the text, instead of having it as an information sign, were on a digital display, so you could set both in a different language, so they both would be in whatever preferred language you choose, would that have helped?

Participant 02 3:42

Oh, yes, 100%.

Annika 3:44

Amazing. Did the puzzle interaction, so the assembly of the statue at the very beginning, feel like a meaningful way to learn, or did it distract you from the information?

Participant 02 3:56

Ehm, I feel like it was interesting to challenge myself to get the pieces together, because, to be fair, they're the same colour, and at first I was messing up with which piece goes where because it's quite a similar pattern in there. So I feel like I was mistaken for a second, but then, eh, I put it in the right place, and the feeling of relief that I was able to complete the puzzle kind of encouraged me to look at this more and like I supported the feeling.

Annika 4:37

How engaging did you find the learning experience in general? So, do you think this engaged you more than if it weren't there and there would have been just the artefact?

Participant 02 4:50

Oh, 100%. I feel like it engaged more than just a statue of the others you cannot touch, and you're like only a meter or two away from it, so you can only take a picture and forget about it. The interactive experience, eh, was actually enjoyable. And I feel like I would remember and recall the information afterwards more.

Annika 5:15

And compared to reading just the standard, you already touched on this, the standard museum information sign, did this feel like a more effective way of learning? And did you learn something that you previously didn't know about this piece of history?

Participant 02 5:30

Well, to be fair, start- starting with I didn't know much about this bit in general at all. I was curious about the Greek mythology previously, but it was mostly Greek mythology, which does not touch the statue and architectural points of it at all. So, that information was freshly new

to me. And as I said before that, I feel like this experience would benefit me more than I would be just take a look at it in museum. I remember the cool marble statue of something from Greece because there was a learning point to it added with different source of information income.

Annika 6:17

And what was the most interesting thing that you looked at, did, read or listened to when you were interacting with the prototype?

Participant 02 6:30

Let me think about it. First of all, I think, I love that it was- the audio was separated by paragraph. So, it's not much like a huge pile of information coming to you, so it's quite easy to perceive. And it's also like in my brain, it's separate, like from where it was. Ehm, so, I think the most interesting information for me was the translation of the word daughters, Korai. I, I translated it to like- There are some similar words that I heard before, and the information was just interesting as it is, because I'm language enthusiast. So, yeah, yeah.

Annika 7:22

Does this experience make you more likely to visit an exhibit about Ancient Greece?

Participant 02 7:28

I adore museums, eh, with interaction pieces in it, because I feel like, for me, it helps to be more like be more focused and curious about that, and was emotional experience. Eh, it's backgrounding in my back of my head, somewhere in subconscious that I did touch it, I interact with that that was a cool experience, and I would most likely to visit more exhibits like that, yeah.

Annika 8:04

Now we're going into the usability part of this interview. Was the purpose of the replica clear before you started?

Participant 02 8:11

Uhm, it is an interesting question, because it was in pieces before and I- as a newcoming guest of the museum, I would not know, what it is. The image representation on the screen helps a lot, but it's still- I feel like before you interact with it, the main idea is not as clear as when you start to do the puzzle.

Annika 8:47

Was it clear that you had to assemble it when you started? Or did you have to look around first?

Participant 02 8:56

Well, the main focus was the stand at the beginning [the wooden base], because, ehm, it's a huge stand with a really highlighted written part, not taking the text. And then you look to your sides, and you see, please touch it. So you're allowed to interact with it. So it's like getting there.

Annika 9:24

Okay, and on a scale from one to five, five being very easy, how intuitive was the statue assembly? And did this help you stay engaged, or did it distract you?

Participant 02 9:39

I would say it was five, ehm, because the magnets do lead the parts to itself. It's not like, you know, in the puzzles, or sometimes the pieces that would suit a couple of places. I felt like this wasn't the same, because the magnets does help to follow the lead. But at the same time, the magnets do connect with different points, but you see the gaps in the statue itself, so you know that it's not supposed to be there. So, I would say that was quite intuitive. Yeah.

Annika 10:18

Would you have preferred it if the puzzle itself were more challenging?

Participant 02 10:25

To be fair, no. I'm like- there is a point to a game to it where you challenge yourself, but it would be- but if it were more complicated and there would be other different objects around, I may give up.

Annika 10:44

And then on a scale from one to five, with five being excellent, how did the material of the statue and the weight of the statue feel to you?

Participant 02 10:55

Quite nice. It was light enough. Would I prefer it to be more heavier? I'm not sure. I can't tell you, eh, for now, but it was quite light and not heavy to damage me, and it was easy to turn around. I was a little bit afraid, eh, to small pieces, to like, press more, to fill the- to fill the grind, whatever the gaps, the dropping points of the outfit. But overall, ehm, yeah.

Annika 11:36

Did the visual and auditory feedback you received feel immediate and logical after placing the statue on the base?

Participant 02 11:43

Yeah, it starts- It starts lighting immediately, which gives me the response that I did place it right, and something is going on, like I activated the mechanism, and I expect something to be forward, and the audio is quite immediate as well, to the point where I can still focus and like be able to understand that something is going on. It's not too rapid for me to be surprised.

Annika 12:13

Was there anything about the physical interaction that was confusing or felt like it could break?

Participant 02 12:21

Well, when I started the puzzle, I saw the little hands, and there was an intrusive thought, where I could, like, if I pressed more, would I break it easily or not? But, yeah.

Annika 12:37

Do you think that this type of exhibit would be suitable for all ages in museums?

Participant 02 12:45

Yeah, but the kids have to be like, they have to be careful about how to not break it within the puzzle, like, how, if you drop it, how easily it will break. It will be interactive and engaging for all ages. I'm sure of that. I just, eh, how it's- how it will be wearable, and how it's usable, and where is the limit to break it. But also, I start to think, if I touch it, how many people before me touched it, as in fact, of germs.

Annika 13:24

Do you have any suggestions for improving the way the information and the replica were presented? Is there anything you do differently next time?

Participant 02 13:34

I was thinking about the more visual on the screen, but now that I think about it, would it distract me from the actual statue? Because when I read the information or hear the audio, I have a minute or so to look at the statue. So I would say, not really.

Annika 14:02

Okay, that is the end of the interview. Thank you very much. Is there anything you'd like to add at this point, or are you happy with what you have said?

Participant 02 14:14

No, I feel like I'm happy I don't have anything to add.

Annika 14:17

Amazing. Thank you.

Participant 02 14:19

Thanks. Bye.

8.8.3 Participant 03

Annika 0:01

Thank you for doing my interview. The purpose of this interview is to gather insights on the prototypes' enjoyment and usability. There are no risks associated with this, and your participation is entirely voluntary, so you have the right to withdraw at any time. So, to start with, what was your general impression of the prototype that you were presented with today?

Participant 03 0:25

It's very professional. Ehm, there's a lot of different things going on, a lot of different aspects. The materials and stuff were very well put together.

Annika 0:40

On a scale, from one to five, with five being excellent, how would you rate your enjoyment of this exhibit?

Participant 03 0:46

Four.

Annika 0:50

Why?

Participant 03 0:50

Urgh, I knew there was a cath. Ehm, I kept wond- not wondering, maybe wondering isn't the word. It's kept you curious kind of the whole time. Kind of all flowed into one, you kind of know what you're doing as it went on. It had some interactive elements putting the thing [the statue] together. There was- you could kind of do things by yourself. There were no set rules, so you had to kind of figure things out on your own. It was good, yeah.

Annika 1:18

What would have made it a five?

Participant 03 1:23

Should have given you a five now hahaha. Ehm, I'd say probably, if it was just like, maybe bigger, it would be more impressive. But for what it is, it's great.

Annika 1:43

Did the puzzle interaction feel like a meaningful way to learn, or was it a distraction from the information?

Participant 03 1:51

No, I'd say, because it's quite kind of heavier, well, a heavier material, but kind of to focus when you're listening. So the interaction kind of kept you listening to what was being said.

Annika 2:03

And how engaging or interesting did you find this learning experience as a whole?

Participant 03 2:10

Eh, I found it interesting. I would never really go and look at this stuff. But then, when you had the whole kind of interaction involved in it, you kind of did- you were kept clued in anyway.

Annika 2:23

Compared to reading a standard museum information sign, did you find this a more effective or engaging way to learn? And did you learn something that you previously didn't know about Ancient Greece?

Participant 03 2:35

Yeah, no, I didn't know anything about Ancient Greece. Yeah, definitely. And I would never really stop, I probably wouldn't stop in a museum to read about it. So when you had your interaction stuff, yeah, definitely more engaging.

Annika 2:48

And what was the most interesting part you looked at, did, read or listened to?

Participant 03 2:56

Ehm, even just putting the girl on the different circles, like you're kind of clued in and you're waiting for what's the next fact kind of thing.

Annika 3:11

Is it piecing everything together?

Participant 03 3:13

Yeah, yeah, it's like a puzzle.

Annika 3:16

Does this experience make you more likely to visit an exhibit about Ancient Greece?

Participant 03 3:22

Yeah, I'd say so. Originally, probably not, but after kind of- you're kind of getting a little snip-pet. So yeah.

Annika 3:30

And then, did you know what the purpose of the replica was before starting?

Participant 03 3:37

No, I did not. I do now.

Annika 3:42

At what point did it become clear to you what you were meant to do with it?

Participant 03 3:48

Ehm, I suppose after reading the whole brief.

Annika 3:52

The "please touch" sign?

Participant 03 3:55

Yes, I caught the “please touch” sign, then yeah, just went from there really.

Annika 4:00

Would you make the “please touch” sign bigger so you know earlier on what you have to do? Or do you think the sign was fine and you just had to walk up to it?

Participant 03 4:11

If you were reading the bits above anyway. I feel like you'd see it. Maybe, if there were a room full of loads of different things, you probably wouldn't read the please touch. But if you're in the same proximity, it kind of catches your eye anyway, when you see a box with stuff in it.

Annika 4:28

You'd say it's fine, the way it is?

Participant 03 4:31

Yeah.

Annika 4:31

On a scale from one to five, with five being very easy, how intuitive was the statue to assemble? And did the game aspect help you focus on the history, or felt like a distraction?

Participant 03 4:43

Yeah, yeah, it definitely was- well, I find it anyway better if it's kind of a game. You're not just in one ear and out the other, you kind of focus and see what to do next. And putting the statue together was fine. It took me a minute or two, like a bit of a challenge as well. I would have hoped to be able to do it. So, yeah, I wasn't gonna give up anyway.

Annika 5:08

So if you were to put a number on it, don't be afraid. I'm not gonna ask you any follow-up questions.

Participant 03 5:14

Okay, five.

Annika 5:17

And then on a scale of one to five, with five being excellent, how did the material and the weight of the statue feel to you?

Participant 03 5:26

I will say four, just because two, I think it was two of them, the light didn't go on. I just had to adjust it [the placement of the statue]. But no, the weight was fine.

Annika 5:36

And then did the visual and auditory feedback you receive feel immediate and logical after placing the assembled statue on the base?

Participant 03 5:45

Yeah, I had to adjust it a little bit, but that could have been on me. I don't know. But it's linked up straight away with the computer and everything as well. So it was instant.

Annika 5:59

And then was there anything about the physical interaction that was confusing or felt like it could break?

Participant 03 6:05

No, no, it's fairly straightforward. And with the computer as well, you kind of get what you're gonna do straight away.

Annika 6:14

And then, do you think this type of exhibit would be suitable for all ages in a museum?

Participant 03 6:20

Yeah, well, I'd say younger probably wouldn't have much- ehh, all the same. They'd probably nearly just play with it. But whether the information went in or not, I'd say that's more of an interest.

Annika 6:34

Then, last question to round it all off: do you have any suggestions for improving how the information and the replica were presented, and is there anything you would do differently next time?

Participant 03 6:48

I don't know, did I see subtitles? I might have. Well, maybe a bigger screen, but we'll take what we can get.

Annika 7:01

I tried. It wouldn't connect to the HDMI.

Participant 03 7:01

HAHA. No, it was pretty good.

Annika 7:09

Perfect, amazing. That was it. If you have anything else to add, let me know. But, yeah, that's it. Thank you.

Participant 03 7:16

Thank you.

8.8.4 Participant 04

Annika 0:00

Hello, and thank you for taking the time to do my interview. The purpose of this interview is to gather insights on the prototypes' enjoyment and usability. There are no risks associated, and your participation is completely voluntary, and you have the right to withdraw at any time.

Thank you for taking part in this research. To start with, what was your general impression of the prototype you were presented with today?

Participant 04 0:27

It was very clear. It was very obvious, visually, I suppose, what you were meant to do and what the purpose was. Ehm, it was clear how you were meant to proceed with the entire operation. Ehm, yeah.

Annika 0:45

On a scale of one to five, with five being excellent, how would you rate your enjoyment of this exhibit? And why?

Participant 04 0:55

Ehm, five? I liked- I liked the interactivity of making the statue. It was enough of a challenge to be interesting. It wasn't super easy and like childlike, but it was something you can do quite easily, and it was clear when you'd clicked everything properly into place. Having the video was really helpful, rather than just reading the information. You're more likely to watch the whole thing and read the entire piece of information.

Annika 1:30

Did the puzzle interaction feel like a meaningful way to learn, or was it a distraction from the information?

Participant 04 1:37

I felt it was helpful. It was like very- you could feel it. I thought it was good. I didn't think it was a distraction, but I did it before interacting with the piece. I don't know if I had interacted with it while it was playing would that- no, you couldn't have done that. Sorry.

Annika 1:59

You could have taken the top part of the statue apart and just put the foot on it.

Participant 04 2:04

I wouldn't have done that.

Annika 2:06

How engaging or interesting did you find the learning experience about the statue's history?

Participant 04 2:15

Very ehm, yeah, like I- I had heard of the statues before this, but I didn't really know that much about them. I knew that there were five in Athens and one in the British Museum, but that was all I knew, and I felt the video was- I was able to learn more about it in an engaging way.

Annika 2:39

And compared to reading a standard museum information sign, did you feel this was a more engaging and effective way to learn? And did you learn something you didn't previously know about Ancient Greece?

Participant 04 2:53

I did, as I said, I only knew those two- those two things as to the location of the statues. I think normally in a museum, you don't really read that much. You skim, and then you walk on. Whereas having an interactive exhibit, you're more likely to stay and experience the full information, rather than just skim the first few sentences and move on.

Annika 3:20

And what was the most interesting thing you looked at, did, read or listened to?

Participant 04 3:25

I think the building of the statue was my favourite part. I liked, I suppose, the challenge level of it.

Annika 3:33

And then, did this exhibit make you more likely to visit an exhibition about Ancient Greece?

Participant 04 3:40

I think so. I think if there were one nearby, I would go to it.

Annika 3:47

And then was the purpose of the replica clear before you started? Did you know what you had to do?

Participant 04 3:59

Yes, it was clear that the statue was in pieces and you were to make it. And the sign of starting here was very clear, obviously, where you were to start. Had that sign not been there, you wouldn't have started in the right place, and you would have gone out of order. But I do think I went out of order on the second part.

Annika 4:21

Yeah, but you are actually okay to go out of order because the clips still make sense. It's just the first one.

Participant 04 4:27

Exactly. So, yeah, yeah, I think it was good.

Annika 4:30

And on a scale of one to five, with five being very easy, how intuitive was the statue to assemble? You already mentioned levels of difficulty, but if you were to put a number on it.

Participant 04 4:42

Like four. There are a few pieces where you have to try a few ways, I think, especially like, I don't know, the mid part, it's very easy to put on backwards or upside down, but, ehm, you know when you've put it in successfully.

Annika 5:03

And then on a scale of one to five, with five being excellent, how did the material and the weight of the statue feel to you?

Participant 04 5:09

I thought it was a really nice weight. There was like a heft to it, I would say five.

Annika 5:17

And then did the visual and auditory feedback you received feel immediate and logical after placing the assembled model on the base?

Participant 04 5:26

I would say so, yeah. It came on within like a second or two of like putting the statue on, and it felt relevant.

Annika 5:39

And was there anything about the physical interaction that was confusing or felt like it could break?

Participant 04 5:47

Nothing felt like it could break. I suppose maybe the clips felt, maybe, after having a very clear starting point, it felt strange not knowing where the next logical step was to go. But as you said, the clips were meant to be more or less watched out of order, so it doesn't matter.

Annika 6:08

And then, do you think that this type of exhibit would be suitable for all ages in a museum?

Participant 04 6:13

I think so, ehm, like maybe not all ages. I feel that if you were a very young child, the statue probably was that bit too difficult. But definitely, I don't know, like, three and up or something.

Annika 6:30

And then lastly, do you have any suggestions for improving the way that information and the replica were presented? And is there anything you would do differently next time?

Participant 04 6:39

The only thing I probably would say is, I didn't notice, like, the box where the statue's in, I didn't notice there was a sign on the box. Like, visually, it was super clear what I was meant to do. But I didn't see there was a sign until afterwards, the “Please Touch” one. I didn't see that at all. But, yeah, no, I think, like as an experience, I think it was very, very good. I don't know if there was much I would improve on.

Annika 7:08

Thank you very much. That was the end of this interview. Do you have anything else to add before we conclude?

Participant 04 7:15

Give Annika an A1 on her FYP, please, Mark, hahah.

Annika 7:19

Hahaha, thank you very much.

8.8.5 Participant 05

Annika 0:01

Thank you so much for taking the time to do my interview. The purpose of this interview is to gather insights on the prototypes’ enjoyment and usability. There are no risks associated with this participation, and it is voluntary, and you have the right to withdraw at any time. Thank you for taking the time. To start with, what was your general impression of the prototype you were presented with today?

Participant 05 0:25

I really liked it. I thought it was really easy to interact with. There was no place where I was like, “Oh, what do I do next?” and it felt like anything that I would encounter in a museum.

Annika 0:40

On a scale of one to five, with five being excellent, how would you rate your overall enjoyment of this exhibit?

Participant 05 0:46

Definitely a five.

Annika 0:47

And then did the puzzle interaction feel like a meaningful way to learn, or did it distract from the actual information?

Participant 05 0:55

No, I wouldn't say it was a distraction at all, because when it's interactive, people are more likely to enjoy what they're doing, because when I see a puzzle, I'm like, “Oh, I can put this together,” or “I'm given the chance to put this together,” so that's what I felt. And after reading about this and the fact that I know something about it beforehand, I was like, “Oh, that's so cool”, and then I saw the puzzle, I'm like, it's an added pleasure, I'd say.

Annika 1:19

And how engaging did you find this overall learning experience, in regards to the statues in history?

Participant 05 1:27

Ehm, really engaging, I would say. Because again, the fact that you get to do something other than just look at it, is a completely different experience in itself. So I'd say it was really engaging.

Annika 1:40

And then, compared to a standard museum information sign, did you think this was a more effective and engaging way to learn? And did you learn something you didn't previously know about Ancient Greece?

Participant 05 1:51

Oh, yes, definitely. I did know about the sisters, but I didn't know what they did or like what values they held. So in that sense, it was really insightful. And yeah, compared to a normal museum experience, this was definitely an elevated one.

Annika 2:08

And then what was the most interesting thing you looked at, did, read or listened to?

Participant 05 2:14

I liked that when we put the statue on the podium, an information system, like a lady, started speaking. So, that was really nice, because you don't often see that in museums unless you have headphones and then you connect them, and then you listen to them. So in that sense, and it's really easy for people who get distracted easily as well, like, oh, if you don't want to read it, you can definitely stay and then listen to what's being said.

Annika 2:44

Does this experience make you more likely to visit an exhibition about Ancient Greece?

Participant 05 2:54

Absolutely.

Annika 2:55

Was the purpose of the replica clear before you started?

Participant 05 3:01

I would say so, yes. I think, from my perspective, seeing that I have an interest in ancient Greek helped as well. And I feel like this would be much more drawn- well, kids would be drawn to it, because they get to put something together. Adults as well, definitely.

Annika 3:17

And then on a scale of one to five, with five being very easy, how intuitive was the statue's assembly? And did the game aspect help you focus on the history, or did it distract you?

Participant 05 3:30

I don't think it distracted me, because I read the information first and then put the statue together. And the thing is, when I was putting the statue together, I did not listen to the woman speaking. So I was like, “Okay, let me hear her again” so I put that back on [putting the

statue back on its spot]. But on the scale, I'd say it was a four. I fumbled just a bit in the beginning when I was putting the, I think, the second piece together [the leg piece]. But other than that, it was nice. It was good.

Annika 3:56

Was it easy for you to figure out how to make the woman speak again? So, how to get the audio back.

Participant 05 4:03

Yes, I'd say so, because I just put the first piece on the podium, and then the light turned green, so I knew that, okay, she's gonna speak now. So that was helpful.

Annika 4:12

On a scale of one to five, five being excellent, how did the material and the weight of the statue feel to you?

Participant 05 4:19

Five.

Annika 4:21

Did the visual and the auditory feedback you received feel immediate and logical after placing the statue on the base?

Participant 05 4:28

Yes, definitely. Everything was- as soon as you did it, you got the feedback.

Annika 4:33

And was there anything about the physical interaction that was confusing or felt like it could break?

Participant 05 4:38

No, I wouldn't say so. The material was sturdy enough that, you know, when you hold it, it won't fall out of your grasp or anything. So, in that sense, it was well built.

Annika 4:46

Okay, perfect. The last two questions, do you think this type of exhibit would be suitable for all ages in a museum?

Participant 05 4:53

Definitely, yes.

Annika 4:54

And do you have any suggestions or improvements for the way the information or the replica were presented? And is there anything you would do differently next time?

Participant 05 5:04

Not really, no, I wouldn't say so, because this is as simple as it can get, and it's really easy for anyone to come and read or listen to it if they don't want to read anything. And yeah, and the statue itself is like, since it's magnetic as well, there's no fear of it falling apart once you put the other pieces together. So that was also a very good idea.

Annika 5:24

Amazing. Thank you. That was it. Do you have anything else to add to this?

Participant 05 5:28

No, this is a brilliant project.

Annika 5:32

Thank you so much.

8.8.6 Participant 06

Annika 0:00

Thank you for taking the time to do my interview. The purpose of this interview is to gather insights on the prototypes' enjoyment and usability. There are no risks associated with this, and your participation is entirely voluntary. You have the right to withdraw at any time. To start with, what is your general impression of the exhibit you were presented with today?

Participant 06 0:25
I feel like it was quite impressive. It does give the museum vibes and the statues- statues vibes, very impressive. I enjoyed it.

Annika 0:41
And then on a scale of one to five, how would you rate your enjoyment of this exhibit?

Participant 06 0:50
Uhm, I would, I mean, first, I'll give it a solid four, but obviously, as time goes on, your attention leads to somewhere else. So, it was a four before, and then kind of went down to a two, three.

Participant 06 1:05
How engaging and interesting did you find the learning experience about the statue?

Participant 06 1:11
It's quite, quite interesting and enjoyable. Since I didn't know any information from these statues before, and I had no prior knowledge of them, but knowing more about them, their history is quite interesting.

Annika 1:23
So, did you learn something you previously didn't know about Ancient Greece?

Participant 06 1:26
Yes, yeah, especially since I'm not very- I'm not very- I don't have much knowledge about, eh, Greek history. I definitely learned one more piece from this.

Annika 1:40
And does this experience make you more likely to visit an exhibit about Ancient Greece?

Participant 06 1:44

Definitely, just knowing that just knowing the history of these- these artefacts or sculptures, and knowing the meaning behind it and why they're here, they have piqued my interest. And now do want to visit one time.

Annika 2:00

And then if you were presented with an interactive museum experience, such as the one I've previously shown you, that allows you to touch the replicas and offers you different information outputs, such as videos and audios in addition to text, would you have enjoyed the exhibit more than this one?

Participant 06 2:18

Definitely, because I feel like with museums, you obviously can't touch the artefacts due to many reasons, but I feel like many people learn more or you- you get more of their attention, if you would use a different, what do you call it, like emotion, like sense, a different sense, like touch, sounds, all this kind of stuff, because with normal museums, though you can't touch, audio could be an option, but yet again, that might not be something you want, but having an interactive artifact like the one you showed me, would be definitely interesting and would gather a lot more attention then.

Annika 2:55

And do you think you would have learned more or been able to recall the information better in the long run, if you were able to interact with the replica and get the information through different outputs, rather than just text and without interaction?

Participant 06 3:09

Definitely, yeah, because people learn from different ways, be visual learner, an audible learner, or just, you know, or both. I feel like having all those options accessible to you, doesn't limit you on one side. So, I feel like it's very open and free to all kinds of people who have different types of learning, learning patterns. I feel like having an inter- having- was interactive with audio, visuals or anything like that would be very helpful.

Annika 3:39

That was it already. Do you have anything further to add before we conclude this interview?

Participant 06 3:47

No, it's very nice. Very good.

Annika 3:50

Perfect. Thank you so much.

8.8.7 Participant 07

ANNIKA 0:00

Thank you for taking the time to do my interview. The purpose of this interview is to gather insights on the prototype's enjoyment and usability. This has no risk associated to it and your participation is voluntary, so you have the right to withdraw at any time. To start with, what was your general impression of the exhibit you were presented with today?

PARTICIPANT 07 0:24

When I was first presented with it, it looked quite interesting. I hadn't seen anything kind of like it before. I kind of went straight for reading the information. I didn't really look at what was happening first. I kind of relied on the reading of information, which kind of halfway through, I found it hard to keep going with reading it as it was a bit kind of wordy, which obviously it's about like different kind of cultures and countries and there was words I didn't understand, so I kind of then just started looking at the things again but I didn't really know what I was looking at, which compared to the interactive design that I was shown I think that would have been a bit easier for me to kind of understand because I would have been more involved in it and known what I was reading or as the voice was talking, I would be able to read at the same time which probably would have made it a little bit easier.

ANNIKA 1:21

Okay, and then on a scale of one to five, with five being excellent, how would you rate your enjoyment of this exhibit?

PARTICIPANT 07 1:29

It was okay. Probably a two because I just found it hard to engage with. I didn't really know what I was looking at and I didn't really know why there was statues there or what was their kind of reasoning. And yeah, like I said before, it was just hard to kind of engage in it. So it's definitely something I'd be interested in and would like be memorable in a museum. But I just found that it didn't really make sense until you read the information, which a lot of people wouldn't do, I guess.

ANNIKA 2:06
And then even with that in mind, did you learn anything new that you previously didn't know about ancient Greece that you'd remember?

PARTICIPANT 07 2:17
Eh, that the top- I thought it was cool that the top of their heads were used to- as like columns or as like structures, which was pretty cool. I kind of- I can't really remember much of the information to be honest, which was, yeah, I can't really remember much. I remember small things, but honestly, I don't really remember much, but it's something I don't really know much about. So, it would kind of pique my interest to then go and learn more. But if I was in a museum with like 50 or 60 other things, I don't think I'd then go home and remember what to even look up.

ANNIKA 2:57
So, picking up from what you said, would it make this experience- would it make you more likely to visit another exhibit about ancient Greece?

PARTICIPANT 07 3:06
I think it would, especially, I think it's cool the way the statues are laid out and it does seem very interesting. It just is a bit overwhelming kind of when you don't know anything about ancient Greece already and then you're reading through the content. It's hard to kind of feel confident that you would know anything to go to a museum. Whereas with something more interactive that you kind of feel involved, it might be a bit easier to learn and then might make- I probably would then be more inclined to like feel more confident leaving a museum where I feel like with this one, with just reading it I wouldn't feel like I learned anything when I was actually there.

ANNIKA 3:47

So, if you were presented with an interactive museum experience, such as the one that I've previously shown you, would you have enjoyed the exhibit more?

PARTICIPANT 07 3:56

I think I definitely would have. It seemed a lot more memorable and I liked the part where you could like assemble the statue. I'd be quite a tactile person and even, as I was saying, I was looking at the details of the statues and how they looked. So, I would remember that more than words. So, I think being able to kind of touch the figures and put them in different places would definitely get my brain going a bit better.

ANNIKA 4:24

Do you think you would have learned more as well and would have been able to recall the information better in the long run?

PARTICIPANT 07 4:31

Yeah, I definitely think I would have been able to- like even now, I forget the information already, to be honest, or even forget the name of what it is. Yeah, so definitely.

ANNIKA 4:43

Perfect. That was it. Do you have anything else to add before we conclude this interview?

PARTICIPANT 07 4:48

No, that's everything.

ANNIKA 4:49

Perfect. Thank you so much.

8.8.8 Participant 08

ANNIKA 0:01

Hello, and thank you for taking the time to do my interview. Your participation is entirely voluntary, and there is no risk associated with this, so you have the right to withdraw at any time. To start with, what was your general impression of the exhibit you were presented with today?

PARTICIPANT 08 0:17

I thought it was very interesting, yeah. I liked it, I guess all the history of it.

ANNIKA 0:25

And on a scale of one to five, how would you rate your enjoyment of this exhibit and why?

PARTICIPANT 08 0:33

I'd say probably a four. I did enjoy it, but I guess after seeing the interactive element, I think that would be a bit more interesting and kind of help break down all the information.

ANNIKA 0:46

And how engaging and interesting did you find the experience and the learning experience in particular about the statue's history?

PARTICIPANT 08 0:55

Yeah, I found it really interesting. I kind of prefer to read things sometimes. So, yeah, I thought all the information was there.

ANNIKA 1:02

Did you learn something new about the ancient Greece that you didn't previously know?

PARTICIPANT 08 1:08

I learned that one of the statues is missing. I didn't know that. And I learned the Greek word for Korai.

ANNIKA 1:18

Daughters and maidens.

PARTICIPANT 08 1:19

Yes, I didn't know that.

ANNIKA 1:21

Does this experience make you more likely to visit another exhibition about the ancient Greece?

PARTICIPANT 08 1:26

Yeah, I think so. I find it interesting.

ANNIKA 1:29

And then if you were presented with the interactive museum experience like I showed you previously, would you have enjoyed the exhibit even more?

PARTICIPANT 08 1:38

Yeah, definitely. I think that kind of brings something new to it. It's a bit different to other exhibits.

ANNIKA 1:43

And do you think you would have learned more or would have been able to recall the information better in the long run if you had the interaction element to it?

PARTICIPANT 08 1:51

Probably, because if there's kind of more short clips, I feel like that stays better. But if you're reading two kind of long paragraphs, that could be harder to kind of remember.

ANNIKA 2:00

That's it already. Do you have anything else to add to this interview before we conclude?

PARTICIPANT 08 2:04

No, thank you for having me.

ANNIKA 2:06

Lovely.

8.8.9 Participant 09

ANNIKA 0:00

Thank you so much for taking the time to do my interview. So, to start with, what was your general impression of the exhibit you were presented with today?

PARTICIPANT 09 0:09

It was interesting. The plaques, I suppose, had different sections, which was nice to read. But I did find myself kind of forgetting what I had just read, moving on to the next section.

ANNIKA 0:21

And on a scale of one to five, with five being excellent, how would you rate your enjoyment of this exhibit and why?

PARTICIPANT 09 0:29

I think it was like a three because it was interesting. I enjoy Greek mythology and things like that. But at the same time [...] I didn't find it very, like- it was something that I would probably see in a museum and keep moving and not remember afterwards.

ANNIKA 0:46

So then on the engaging and interesting part, how did you find this learning experience about the statue?

PARTICIPANT 09 0:55

I thought it was interesting, but I think knowing that there was an interactive one, I think I could have learned a lot more and remembered a lot more if I had interacted with the exhibit more.

ANNIKA 1:05

And does this experience want to make you visit another exhibit about ancient Greece or more likely to visit an exhibit about ancient Greece?

PARTICIPANT 09 1:14

Like I said, I'm a huge Greek mythology fan, so I think I would, but specifically this exhibit, probably not interacting with it wouldn't have- I don't think I would have gone again, something about that specifically.

ANNIKA 1:29
And then, if you were presented with the interactive museum experience that I previously showed you, would you have enjoyed that a bit more?

PARTICIPANT 09 1:37
Yes, I like interacting with things and I'm very like, audio is very important for retaining information for me. So, I think I would have enjoyed it and I think it's really fun getting to feel like you're a little bit of a part of it and putting things together.

ANNIKA 1:51
So, you would agree that with the interactive experience, you would have been able to learn more and recall information better in the long run.

PARTICIPANT 09 2:01
Yes, I think so.

ANNIKA 2:02
Yeah, perfect. That is it already. Do you have anything else to add before we conclude this interview?

PARTICIPANT 09 2:09
I don't think so.

ANNIKA 2:10
Perfect.

8.8.10 Participant 10

ANNIKA 0:01

Thank you for taking the time to do my interview. To start with, what is your general impression of the exhibit you were presented with today?

PARTICIPANT 10 0:10
I really liked it. Very informative. The text wasn't too long. It wasn't too technical either. I hate that in museums when you don't understand what you're being told. And I like the exhibit, especially where there was no extra statue in the middle, because it was confusing, so I wanted to read.

ANNIKA 0:30
And on a scale of 1 to 5, with 5 being excellent, how would you rate your enjoyment of this experience and why?

PARTICIPANT 10 0:39
Honestly, a 5. I love Greek history, so that's probably part of it. I tend to get quite bored in museums, but I found that this, like I said, it wasn't too long, it wasn't a boring text, and it's right there in front of you, rather than behind a thing of glass or something, so I really liked it.

ANNIKA 1:01
And how interesting did you find the learning experience about the statue's history?

PARTICIPANT 10 1:07
Very. Yeah, I mean, it included a lot of different things. Like you had the language, you had the structural element, like commentary on the history as well. So, it wasn't like you were just reading an architectural thing. So, I liked it.

ANNIKA 1:21
Very good. Does this experience make you more likely to visit an exhibit about ancient Greece?

PARTICIPANT 10 1:27
Yeah, I would say so. Like I actually learned, and sometimes I feel like in museums I don't, so.

ANNIKA 1:32

And if you were presented with the interactive museum experience that allowed you to touch the replica of the statues and offer different information outputs such as video and audio in addition to the text, do you think you would have enjoyed the exhibit more or found it more as a distraction?

PARTICIPANT 10 1:52
I think I would have found it enjoyable, but I wouldn't have learned as much, especially if there's multiple people doing it, because then you're just hearing the audio repeating all the time. So I think I would have learned less, but I would have still really enjoyed it.

ANNIKA 2:04
Okay, and how about your recall? Are you someone that can recall information very well by just reading it, or would you have supported the idea of having a different output of information?

PARTICIPANT 10 2:22
Usually, I'm pretty good with just reading, so I would say this was good for my way of learning, I think.

ANNIKA 2:29
Very good. That's the end already. Do you have anything else to add to this interview before we conclude?

PARTICIPANT 10 2:35
No, I really liked it.

ANNIKA 2:37
Perfect.

8.8.11 Participant 11

ANNIKA 0:00
Thank you so much for doing this interview.

PARTICIPANT 11 0:02
You're so welcome.

ANNIKA 0:03
So, to start with, what was your general impression of the exhibit you were presented with today?

PARTICIPANT 11 0:09
Yeah, my first impression was that it was very modern looking, very professional, very clean. Very what I expected in a museum.

ANNIKA 0:31
On a scale of one to five, with five being excellent, how would you rate your enjoyment of this exhibit

ANNIKA 0:36
I would give it a 2.5 out of 5, or 50% of the full 100. Just because I enjoyed it, I felt as if I was reading it, I was learning something, but I didn't remember anything. And I like that, you know, when you go to it, there's like text there, and it kind of makes you, you know, you just have to read it, you have to pause. And yeah, compared to the other one, though, I would enjoy the interactive one more just because it's more interactive and it kind of would pique my interest more. And I think I would remember and retain the information better just because it would trigger my brain to be working.

ANNIKA 1:31
So, when you said you don't remember anything, is it the information from when you had to do the quiz? Were you struggling to answer?

PARTICIPANT 11 1:38
Yes, I was struggling to answer. I could remember like how the statue looked, you know, like the braids detail, like the way they had their leg kind of bent but I couldn't remember anything specific about it yeah.

ANNIKA 2:00

How engaging and interesting did you find the learning experience in particularly about the statues history?

PARTICIPANT 11 2:12

I enjoyed it. I wouldn't say I really, really, really enjoyed it. It was nice. I did like that, you know, with the descriptions on like the hair and like bent and how the statues looked that as I was reading the sentence, I would look up at the statue. So, I found that engaging. It's just that coming out of it, I didn't really remember why they look a certain way or they have the hair a certain way. Whereas with the other installation, it would probably have triggered my memory better just because I would be engaging with it. Just being more interactive helps me retain information better.

ANNIKA 3:05

You said that you don't remember a lot about what you read, but when you were reading it, did you learn something that you previously didn't know about ancient Greece?

PARTICIPANT 11 3:16

Yes, when I was reading it, I did learn something new. That's why I found it interesting because I didn't have any information about this prior to it. I just don't remember it.

ANNIKA 3:28

And does the static experience make you more likely to visit an exhibit about ancient Greece?

PARTICIPANT 11 3:36

It doesn't make me excited. It's not something I'm thinking in my head, yes, I want to have to do this. But I do like going to museums if I'm visiting another country just for tourist purposes. But it wouldn't be something that it's like me, myself, as a hobby or pastime, like, “Oh, I enjoy going to a museum.” Whereas with the other installation, for me, I think that it could possibly trigger or just make me want to go to a museum more because it's something new and different and it's interactive. It's not just- I'm not just looking at something. I'm actually participating in it like. I'm low-key in a way kind of diving into the culture and the history, if that makes

sense. So yeah, it would be something that I talk about for sure if I went to the interactive Installation.

ANNIKA 4:28

So, you already touched on this, but just to kind of summarise it up, if you were presented with this interactive museum experience that allows you to touch the replicas of the statues and offer different information outputs such as videos and audio in addition to the text, would you have enjoyed the exhibit more?

PARTICIPANT 11 4:45

100% I would have enjoyed it more. I would have spoken to a lot of people about it and I think my friends and family would be interested in going. I think I could see this being- I can see this being an opening door for museums. Just to get more people going in there besides like tourists, as you know, during like lower peaks or whatever. Yeah I 100% would enjoy this [the interactive exhibit] more.

ANNIKA 5:10

Do you think you would have learned more or would be able to recall the information better in the long run?

PARTICIPANT 11 5:18

Yeah, I do believe I would be able to remember the information better just because I would spend more time on this installation for sure. Just being as I'm building the model and I'm looking at the screen and it just looks cool and it just- It makes you want to walk over and if two of them were placed in the same room I would be more drawn to go to the interactive one just because it looks- It's different. It looks fun. It is fun. Yeah, 100%.

ANNIKA 5:52

Perfect. Amazing. Thank you. That is the end of our interview. Do you have anything else to add?

PARTICIPANT 11 6:02

No.

ANNIKA 6:03

Thank you so much.

PARTICIPANT 11 6:05

You're so welcome.

8.8.12 Participant 12

ANNIKA 0:00

Thank you so much for taking the time to do my interview. To start with, what was your general impression of the exhibit you were presented with today?

PARTICIPANT 12 0:13

I didn't know anything about the statues itself. I knew when I was looking at it, I was like, "why is there a gap?" But it was explained in the written piece. I thought it was interesting that you included the number, like the years on the actual name of the thing [the Caryatids]. That was interesting, that was quite a while ago. Yeah, solid statues.

ANNIKA 0:41

And on a scale of one to five, with five being excellent, how would you rate your enjoyment of this exhibit?

PARTICIPANT 12 0:49

If I was imagining myself in the museum actually coming up to this big massive thing, probably a four. Like that was actually really interesting. Even just the- the contrapto thing [Contrapposto pose], I was like, that's crazy. I didn't know that was a thing. I did fear when I walked away, I didn't retain as much of the information as I thought I might have. But yeah. Wait, did I even rate it? I don't remember. I will say three.

ANNIKA 1:21

How engaging or interesting did you find the learning experience about the statue's history?

PARTICIPANT 12 1:27

I actually really liked it. I felt like the written text wasn't so long that I was getting bored. When I first looked at it, I did think it was going to be a bit much, but then when you actually read it, it's not that bad and the language isn't too hard. Which, I mean, I'm able to read it. It is something that is important for anyone walking up, like if there was a child walking up, they'd be able to understand just as well as I did.

ANNIKA 2:02
And then did you learn something you didn't previously know about ancient Greece?

PARTICIPANT 12 2:09
Yes, I want to say. I don't know what the question with the punishment, I couldn't remember that being so honest. I hate women being punished. I learned about that they were the daughters of [...]

ANNIKA 2:25
Athens.

PARTICIPANT 12 2:26
Athens! Ah, that was close. And I liked that it had- it mentioned the fact that one of them is in a British museum and that they keep it open in the hopes that she'll someday come home.

ANNIKA 2:40
And does this experience make you more likely to visit an exhibit about ancient Greece?

PARTICIPANT 12 2:47
I love ancient Greece anyways, so- but yes.

ANNIKA 2:55
And then if you were presented with the interactive museum experience that allowed you to touch the replica of the statue, offer different information outputs such as videos and audio in addition to text, would you have enjoyed the exhibit more or would you think that was more a distraction?

PARTICIPANT 12 3:11

Definitely would have enjoyed the exhibit more because in my mind the museum I'm in- I feel like that probably isn't something that's available at every single one. And when you've already been through a museum, like you do start kind of shutting off and just having a look, not caring about the actual learning aspect. But that would have been really fun. I would have loved putting it together.

ANNIKA 3:41

Do you think you would have learned more or would have been able to recall the information better if you had the interaction?

PARTICIPANT 12 3:47

I definitely would have been able to recall it better. Just even like the getting to put it together yourself and like moving it to the different spots. Like I feel like it would split the information up in my head a bit better.

ANNIKA 4:01

Okay, perfect. That's the end of the interview. Do you have anything else to add before we conclude?

PARTICIPANT 12 4:10

Nope.

ANNIKA 4:10

Perfect.

8.8.13 Participant 13

ANNIKA 0:00

Thank you for taking the time to do my interview. The purpose of this interview is to gather insights on the prototype's and enjoyment usability. There are no risks associated with this study and your participation is voluntary, so you have the right to withdraw at any time. To start with, what was your general impression of the exhibit you were presented with today?

PARTICIPANT 13 0:21

I really liked it. I liked the interaction thing. I like being able to put the pieces together, like the puzzle. The one thing I think if I was in a museum, I'm more of a reader than a listener. So that's the one thing. I don't think I would have read it all if I'd known that it was just going to- I didn't realise the words were going to be the ones that were in front of me [talking about the fact that the audio was the same text as the information sign text]. I wouldn't have read it all. If I had realized that the words would have been the same but I do really like the interactive element. I think it's really fun and I also am aware that I'm an outlier like I'm the type, I go into a museum and I read like every single paragraph like OCD level. I can't leave before I read everything so- well personally I'm more of a reader I think it was really cool and I liked the different like- the moving it around and everything. I think- I think it was nice because it kind of keeps your attention like short and sweet and then it's like move on to the next one- you know there's like- I feel like if in a different world, if you had someone and they're like, you know, you press a button and then it speaks for like 10, like five minutes, you're like, "Oh my God, would you ever shut up?" You know, at a certain point, but with the interaction stuff it's very like- the little gaps kind of make it more I don't know like you take in more I think [talks about the seperation of the text into multiple audio clips]. Does that make sense?

ANNIKA 1:39

That does. Moving on, on a scale of one to five, with five being excellent, how would you rate your enjoyment of this exhibit and why?

PARTICIPANT 13 1:46

I liked it. In terms of the general history, oh sorry five. I like I found I like history. I find it- I found that part really interesting anyways like it is something I would stop to read in a museum regardless. But I do, like I said, I really like the interactive elements I think it makes it a bit fun. And it's sort of- it's probably more appealing as well to people who wouldn't stop to read every exhibit. That would be how I'd see it. I also think it's nice, like when I go to the museum, I usually go by myself because it's like, I want to stop and read everything and not everyone wants to do that. And I think that interaction element is nice because it would mean that if I was with someone else in a museum, that there'd be more of like, you know, you're listening together. I think there should be more of that if you're trying to like spend time with someone in the museum, if that makes sense. Because that's something I'd probably be more inclined

to do if I was with other people rather than like, you know, "Okay, sorry, just like stand there for a second while I read all of this." We can stand there together and listen, you know, like it's, I think that's nice. And it also means that it's- it'd be more- I can't think of the word, but like, if you had a big group of people and it was something like this, which is like really famous and loads of people want to see it that like you know one person can like do that thing and everyone else is able to listen. It's not like you're standing there like "Oh I want to read that paragraph but that person is taking seven years to read that." You know like it's- I think it's more accessible to a bigger group of people which is nice. I like that.

ANNIKA 3:17
That is a nice way of thinking of it. And I think that might have been the word you were looking for, the engagement of it. How engaging or interesting did you find the learning experience about this?

PARTICIPANT 13 3:26
I really liked it. I like that it's like- even what the exhibit was saying about like the folds and the braids and blah, blah, blah, like even looking at those, which I assume that's what she would have looked like once upon a time, as opposed to, you know, thousands of years breaking it down or whatever. Like I liked being able to see the like intricate- intricate- I can't speak English, I'm so sorry. I like being able to see all the intricate little details. Like, being able to look at that.

PARTICIPANT 13 4:01
So it was really interesting to be like, "Oh, all of, like, those folds and stuff, like, they like added structural support" and like all that like being able to see it. I really liked that there was like a tangible thing you could hold, you could feel it, you could sort of interact with it and I really liked that. I thought it was really cool because it really lets you like get up close and personal with it and really like see all the little bits and bobs that you don't really see unless you were like an architect or whatever usually which I really liked.

ANNIKA 4:26
And did you learn something you previously didn't know about ancient Greece?

PARTICIPANT 13 4:30

I did. Maybe not about ancient Greece, but like more specifically. I was aware that they were sisters and I was aware that like one of them had been kidnapped from the other five. But I didn't know that what they were meant to represent was the women who betrayed Greece and like all that little bit of history. I didn't know. And if I was in a museum and I had just like walked past them and I'd be like, "Oh, I know that." I liked- I learned something new, which was really nice. I like learning something new. But- and I think the engagement thing made it out, so you also pay more attention to the fact that you're learning something new if that makes sense.

ANNIKA 5:04

And did the puzzle interaction feel like a meaningful way to learn or was it more a distraction?

PARTICIPANT 13 5:10

I liked it. I liked being able to put the pieces together. It was fun. I think it's definitely something, if I was thinking about it, like something that would appeal to kids. You get to the puzzle and then it's like, oh, blah, blah, blah, blah, blah. But personally, I like the puzzle. I like doing stuff with my hands. And also it's like that other thing as well where you really get to know the statue as you're putting it together, which I think is nice. Although I would wonder if some people wouldn't be bothered because they're like, "Oh fuck, I have to put it together first." So there's one thing that would occur to me, but it's not something that I would feel personally.

ANNIKA 5:49

Compared to reading a standard museum information sign, do you feel like this was a more effective way to learn?

PARTICIPANT 13 5:56

Yeah. Like I said, I'm very much like I would read every paragraph but I know I'm an outlier in that as a general concept I think it would be a more effective way to learn. It's more accessible more people can engage with it at one time than just like reading a little paragraph on a museum sign. As a personal thing, I would kind of be more of the reader. Like I said, I am more of a reader than a listener. But as a general sort of rating the overall effectiveness of it, I think I liked it. I thought it was a good experience.

ANNIKA 6:27

And what was the most interesting thing you looked at, did, read or listened to?

PARTICIPANT 13 6:35

That's a good question.

PARTICIPANT 13 6:37

I think the most interesting thing to me was, well, firstly, the new bit of history I learned. But I think, like I said, the intricacies, being able to tangibly touch it and see all the, like- it's one thing to be told, like, "Oh, the folds in the dress supported the blah, blah, blah." It's another thing to be like, "Oh, I can feel it, I can see this. I can turn it and see how that works," you know? I liked that. I liked being able to do that. That was my most interesting thing, I think.

ANNIKA 7:03

And then does this interactive experience make you more likely to visit an exhibit about ancient Greece?

PARTICIPANT 13 7:09

I think so.

PARTICIPANT 13 7:17

I like ancient Greece. I would probably go anyways, but I think it would be more likely to- If it was like at the end of a long museum day and you're like, "Oh, I want to see this exhibit, but like my brain is tired, blah, blah, blah." And I do. do want to see this but like I think it would make me more likely to engage rather than just sort of like walking past me like "Okay I've seen it bye" you know. For me, like I said, I like being able to read it but I don't like at a certain point when your like brain is fried, I think the interactive element and being able to listen to it I think would make a difference and like I said I think the little like- the fact that you're interacting with it constantly to move it around and all that stuff, it will keep your brain more engaged so I think that's it, yeah. However, would it make me more likely to visit an exhibit about like war, which I have no interest in? Yeah, I do think so.

ANNIKA 7:57

We are now going to move on to the usability part of the interview. So, when you walked up to it was the purpose clear of the replica

PARTICIPANT 13 8:07

I think so. Yeah. I think it might have taken me a second. If I was completely unaware, it might have taken me a second to be like, "Oh, like X plus Y equals Z" but I think it's fairly clear. And also I would assume that in an actual museum, like the sign would be bigger. Like it would all be a bit bigger, which would make it the clearer thing as well.

ANNIKA 8:43

On a scale of one to five, with five being very easy, how intuitive was the statue to assemble?

PARTICIPANT 13 8:50

Oh five.

ANNIKA 8:52

And did the game aspect help you focus or distract you?

PARTICIPANT 13 8:56

I liked it. I thought it was fun. Like I've said, like 75 times at this point, I really liked being able to like tangibly put it together. I enjoyed that part. I liked it, yeah.

ANNIKA 9:07

And then on a scale of one to five, with five being excellent, how did the material and the weight of the statue feel to you?

PARTICIPANT 13 9:16

I will be perfectly honest, I didn't really pay attention that much to it. I guess like a five, I didn't really notice anything that made me go like, "Oh, I don't like this." You know, like it's not really something that occurred to me to think about, to be honest.

ANNIKA 9:31

But that's good as well because usually if something is negative, you remember it.

PARTICIPANT 13 9:35

No, exactly. Like, that's what I'm saying. Like, it's a five because if it was like a weird weight or it was like weirdly, you know, feeling on my hands or whatever, I probably would have noted it in my brain, whereas I didn't think about it at all. So, yeah, five.

ANNIKA 9:50

And then did the visual and auditory feedback you received feel immediate and logical after placing the assembled statue on the base?

PARTICIPANT 13 9:58

Yeah, I think so. I will say I was kind of in my head a little bit going like, I think this is where I'm going next. But yeah, I think it kind of- it made sense.

ANNIKA 10:09

You are allowed to place it, except for the first one, wherever you want. They still make sense, each of the clips. But it's just then you're out of order with obviously the written part. But besides that, it makes total sense to go in whatever direction you want.

PARTICIPANT 13 10:23

Yeah.

ANNIKA 10:24

And then was there anything about the physical interaction that was confusing or felt like it could break?

PARTICIPANT 13 10:30

No. Oh, I think when I was first putting it together, the arm, her arm, like I couldn't get the skirt in right because her arm was kind of in the way of it. So that was- like that took me a second. But like other than that, I think it's fairly straightforward.

ANNIKA 10:45

Do you think that this type of exhibit would be suitable for all ages in a museum?

PARTICIPANT 13 10:49

Oh, absolutely. It also felt like very- actually going back to the material, it felt sturdy. Like it didn't feel like something I was going to break by like moving in a certain way or whatever. Like it feels like something that I would if I had children, god forbid, it was something I'd be like "Yeah you can go pick that up, you can go touch it." You know like it's- it felt sturdy and it felt like you know if I had a child, God forbid, and I was taking them to a museum, it's something that I would like to see, you know.

ANNIKA 11:18

And do you have any suggestions for improving the way the information or the replica were presented? Or is there anything you would do differently next time?

PARTICIPANT 13 11:30

It's a good question. Honestly, the only thing is just like, you know- which is obviously not something you could have done now- it's just like making it all a bit like bigger. But like that's also- that's not something like- as in having a sign, the "please touch" sign. I didn't even see the "please touch" sign until after I'd already like done the whole shebang. Like making all the signs a bit bigger, but that's not really something you could do here either. So yeah.

ANNIKA 11:54

Perfect. That's the end of the interview. Do you have anything else to add before we conclude?

PARTICIPANT 13 12:00

No.

ANNIKA 12:02

Thank you very much.

8.8.14 Participant 14

ANNIKA 0:00

Thank you so much for taking the time to do this interview. So to start with, what was your general impression of the exhibit you were presented with today?

PARTICIPANT 14 0:09
I think it's very innovative and something that I would definitely walk towards straight away in a museum as opposed to just looking at something static. Because I'm not a massive museum person, but that would interest me.

ANNIKA 0:23
And on a scale of 1 to 5, with 5 being excellent, how would you rate your enjoyment of this exhibit?

PARTICIPANT 14 0:28
5.

ANNIKA 0:29
Very good. How engaging and interesting did you find the learning experience of the statue's history?

PARTICIPANT 14 0:36
Very much, actually, more than normal because I read the stuff first because I didn't realize I would be hearing the same information again. But because of that, it kind of reinforced what I had read already. So I actually paid more attention and remember significantly more than I normally would. So, yeah.

ANNIKA 0:54
Did you learn something you didn't previously know about ancient Greece?

PARTICIPANT 14 0:58
Yes, everything. I didn't know any of that, which is really cool. And now I want to visit, so here you go.

ANNIKA 1:04

Next holiday destination.

PARTICIPANT 14 1:05
Absolutely. Summer 2026.

ANNIKA 1:09
Did the puzzle interaction feel like a meaningful way to learn or was it a distraction from the information?

PARTICIPANT 14 1:16
I think it was meaningful because the information talks about details of the statue and stuff. So when you're picking something up and putting it together, the 3D print is really good as well. So you can see the drapes and all the other little details that they were mentioning, the bent leg and the thing on the head. So I think it added to it. It didn't take away anything.

ANNIKA 1:35
And then compared to reading a standard museum information sign, did this feel like a more effective and engaging way to learn?

PARTICIPANT 14 1:42
Yes. Yes, because A, I don't know if I would stand and read everything normally, but because the whole thing was like, "Ooh, what's that?" So, yes, this was a lot more engaging.

ANNIKA 1:52
And then what was the most interesting thing you looked at, did, read or listened to?

PARTICIPANT 14 1:57
I loved putting it together, which might be an ADHD brain thing, but I did like putting it together because suddenly there's something to do rather than just observe because museums are very observational. So if people are not really fans of it, I think this is a great way to get people going to them.

ANNIKA 2:14

And then does this experience make you more likely to visit another exhibit that might have the same kind of installation?

PARTICIPANT 14 2:21

Yes, absolutely. I would love to go to a museum with this stuff in it. I think I would learn so much more. Because you walk around, you're paying attention for the first five minutes, and then at the end of it, you just don't know what the last half an hour was. But I think this is very engaging. And on a complete side note, we need to go to the London Museum and look at the missing sister. I think that would be really cool. Yeah.

ANNIKA 2:45

Now we're moving on to usability. So when you walked up to this exhibit, was the purpose of the replica clear before you started? So did you know what you kind of had to do?

PARTICIPANT 14 2:55

On an objective level, yes, but I also think because it was on the left and I'm just- brain's just designed to go from right to left, I read everything before I thought of putting it together and then the same information was relayed back to me. So maybe that being on the left would make more sense to me because that's just how I would go. But I suppose it depends on what way people are entering into a room.

ANNIKA 3:16

And on a scale of 1 to 5, with 5 being very easy, how intuitive was the statue to assemble?

PARTICIPANT 14 3:22

Oh, 5.

ANNIKA 3:23

And then did the game aspect help you focus or felt like a distraction?

PARTICIPANT 14 3:28

Oh no, it helped me focus because again the details and stuff are really good. And because I had read it before it kind of made more sense and then I heard it again. So it was, yeah, it definitely added to it.

ANNIKA 3:38
And on a scale of one to five, with five being excellent, how did the material and the weight of the statue feel to you?

PARTICIPANT 14 3:44
Oh yeah, five, because it's all lightweight. It's 3D printed. It's great. Yeah.

ANNIKA 3:49
Did the visual and auditory feedback you received feel immediate and logical after placing the assembled statue?

PARTICIPANT 14 3:57
Yes. Again, the only thing there was that I had read it already and then I put it together and yeah, I moved left for some reason. So the last paragraph started playing but it was very obvious that that was not the order it was meant to be going in.

ANNIKA 4:10
The order is a bit- it's like 50-50 how you want to do it. All the clips make sense.

PARTICIPANT 14 4:16
Yes.

ANNIKA 4:16
Played in whatever order you want.

PARTICIPANT 14 4:18
True.

ANNIKA 4:20

But obviously, if you print it, you have to put it in some sort of order.

PARTICIPANT 14 4:24

Yes, of course.

ANNIKA 4:25

And for the audio and text actually to make sense with the statue placement. The last one kind of had to be the middle one where there's none.

PARTICIPANT 14 4:33

Yes.

ANNIKA 4:34

So that was kind of the idea behind it. But you picked up based on the observation very quickly.

PARTICIPANT 14 4:41

It started speaking and I was like, "Nope, that's not right." I was just like, will it still keep playing if I pick it up? That was my only moment of hesitation. But of course it stopped. So well thought out.

ANNIKA 4:52

Was there anything about the physical interaction then? Did anything feel like it could break?

PARTICIPANT 14 5:03

No. No, no, all good. All good. Yeah, I just- would like is the idea for it- would the size be that small and interactive for the person and then would the statue still be in the back is that the idea?

ANNIKA 5:15

So, the idea is that this would be the the original [pointing at the video screen].

PARTICIPANT 14 5:19

Yeah.

ANNIKA 5:19

And then the kind of spotlight and the interactivity would interact with the original and not with a video screen

PARTICIPANT 14 5:27

Oh yeah. Gotcha.

ANNIKA 5:27

Because you want to draw the eye back to the original. So, you're not stuck on the replica because you're there to see the original.

PARTICIPANT 14 5:34

Yes that makes sense.

ANNIKA 5:39

And then do you think that this type of exhibit would be suitable for all ages in a museum?

PARTICIPANT 14 5:45

Yes, actually. It will get kids into it more and older people that are not into it as well. It will bring them back to it. So yes.

ANNIKA 5:52

Do you have any suggestions for improving the way the information and the replica were presented? Is there anything you would do differently next time?

PARTICIPANT 14 6:00

Literally, the only thing is the order thing because I think we just- because of English as well you go everything left to right so that is the only reason I read everything that was there and then went to the box and the "please touch" sign as well because museums you're so careful of not touching anything I might just put that as a little thing in the back. Instead of it being down there. That's the only thing, yeah.

ANNIKA 6:23

Perfect. That's the end of the interview. Do you have anything else to add before we conclude?

PARTICIPANT 14 6:27

Uh, no. I think I got everything in.

ANNIKA 6:30

Thank you.

PARTICIPANT 14 6:31

Thank you.

8.8.15 Participant 15

ANNIKA 0:00

Thank you so much for taking the time to do my interview. The purpose of this interview is to gather insights on the prototype's enjoyment and usability. So to start with, what was your general impression of the exhibit you were presented with today?

PARTICIPANT 15 0:14

The general impression?

ANNIKA 0:15

Yes.

PARTICIPANT 15 0:15

I thought it was very fun and interactive. It taught me a bit about history anyways. And yeah, no, I think it was really good.

ANNIKA 0:27

On a scale of 1 to 5, with 5 being excellent, how would you rate your enjoyment of this exhibit?

PARTICIPANT 15 0:33

I would rate it 4. I think it was very fun and interactive and very simple. However, if I was in a museum, like, you know. Depending on the content like this is very nice to look at however I wouldn't say that it was fantastic or mind-blowing in a way but it was very enjoyable.

ANNIKA 0:57

And how engaging did you find the learning experience about the statues' history?

PARTICIPANT 15 1:04

I felt that it was engaging. [...] Yeah, no, I felt like it was very engaging. I think I was just a little bit more curious with like putting it together and distracted by that at one point though. So, and then how it, like- I was curious on how it actually worked when I put the statue on different areas and see if it all worked and like you know came out and like told me all the information but yeah no it was really engaging.

ANNIKA 1:36

Do you think it would have benefited from a sign that explains like the technology behind it?

PARTICIPANT 15 1:47

I don't think that would be necessary. I think it would be very nice because I haven't seen this technology as often in museums. So if this was something new, then yeah, I think that little sign would be lovely just for maybe some context. However, I don't think it's necessary. Yeah, no, I think just saying, like, put the statue there and then just keep going around, that's perfectly fine. But if it's something novice in museums, just like maybe as a once-off to introduce the whole idea, that would be nice for people who are interested.

ANNIKA 2:29

And then did you learn something you didn't previously know about the ancient Greece?

PARTICIPANT 15 2:33

Oh yeah, I learned about the women who, what were they called again?

ANNIKA 2:41

Caryatids.

PARTICIPANT 15 2:42

Caryatids. I haven't heard about them before so it was nice learning a little bit more about that.

ANNIKA 2:48

And you already touched on this, but the puzzle interaction, did that feel like a meaningful way to learn or a distraction from the information?

PARTICIPANT 15 2:55

I felt personally it was more of a distraction because it took me a minute or two to put it together and then I was like okay cool let's let's see how it works after that but you know yeah.

ANNIKA 3:15

Would you think that it wouldn't have been as much as a distraction if the video and the audio would only play if you had correctly assembled the statue? So, you place the foot on first, if it wouldn't have played, like the green light wouldn't have turned green, would that have helped you to not be as distracted?

PARTICIPANT 15 3:36

I think so because when I started, as you said before, I put the foot on first and it seemed to work wholeheartedly. And then I realised, oh wait, no, I had to assemble the statue. Maybe that distracted me a bit, so I think it would be a lot cooler if it only work once the statue was assembled. I don't know, I think humans are simple beings and the whole idea of assembling a statue for the exhibit to work might, you know, complicate it a tiny bit.

ANNIKA 4:21

Okay, and compared to reading a standard museum information sign, did this feel like a more effective, engaging way to learn?

PARTICIPANT 15 4:29

Oh, completely. Definitely because you're actively interacting with it and you're placing it, listening to it once it starts and stops. Like, you're actively wanting to search for different- more

knowledge, really. I think it's more fun. Maybe if it was like maybe a video on the screen that could also increase engageability because it reminds me of like when you go into a museum and you sit down and watch a video. It's kind of that experience.

ANNIKA 5:04

The original idea is that this would be the actual artifact [pointing at the video screen] and that a spotlight would be drawn based on like where you place the statue. So, your eye is drawn back to the original because you're there for the original, not for the replica. But obviously we're lacking the original here.

PARTICIPANT 15 5:23

Ah, that makes more sense.

ANNIKA 5:23

What was the most interesting thing you looked at, did, read or listen to?

PARTICIPANT 15 5:29

I think the whole idea of assembling it together and just putting it around is the most interesting to me because I haven't interacted with something like that before in a museum setting. So I think the experience of doing it was quite enjoyable. The history itself is nice to know, but, like, you know, in terms of, like, my interest level in ancient Greek, there's not much there, I have to say.

ANNIKA 6:00

Does this experience make you more likely to visit another exhibit that has this type of interaction?

PARTICIPANT 15 6:05

Oh yeah, I think it's nice to have it in an exhibition, especially when it comes to artifacts, yes.

ANNIKA 6:11

And when you walked up to it, was the purpose of the replica clear, so what you were meant to do with it?

PARTICIPANT 15 6:21

I had an idea of what to do.

ANNIKA 6:28

On a scale of one to five, with five being very easy, how intuitive was the statue to assemble?

PARTICIPANT 15 6:34

Oh, like, I'd say- five is easy?

ANNIKA 6:38

Yes.

PARTICIPANT 15 6:39

I'd say a little bit- like, four. Like, maybe I had to take an extra minute or two because one piece was upside down, but, you know, it was easy enough.

ANNIKA 6:49

And then on a scale of one to five, with five being excellent, how did the material and the weight of the statue feel to you?

PARTICIPANT 15 6:58

The material, it actually felt very good.

PARTICIPANT 15 7:05

I wouldn't say like five, but I would definitely say four because, you know, it felt like, you know, professional. It felt like, you know, sturdy. It felt like, you know, it served its purpose. I would say if you wanted- if this were to be in an exhibit, I would hope for it to be a little bit more heavy. And that's just like a little bit more. Not like, you know, nothing too big. But, you know, just so you can actually, like, you know, feel like it's sat you.

ANNIKA 7:36

Did the visual and auditory feedback you received feel immediate and logical after placing the assembled puzzle onto the base?

PARTICIPANT 15 7:42
Oh, yes, definitely.

ANNIKA 7:43
Was there anything about the physical interaction that was confusing or felt like it could break?

PARTICIPANT 15 7:49
No.

ANNIKA 7:50
Amazing. Do you think this exhibit would be suitable for all ages in a museum?

PARTICIPANT 15 7:57
The assembly part could be messy because I feel- I can see child just throw it across the room and it'd break and then go all over the place. So, maybe from like 13 upwards it should be fine. But like just in case, you know.

ANNIKA 8:15
Do you have any suggestions for improving the way the information or the replica were presented? And is there anything you would do differently next time?

PARTICIPANT 15 8:24
I would read the sign. My only gripe would be the assembly of the statue because, as before said in this interview, it did distract me a little bit. I think the statue itself is a very good idea and it's very useful in this exhibit.

ANNIKA 8:29
Thank you so much. That concludes our interview. Do you have anything else to add?

PARTICIPANT 15 8:32

No, thank you so much.

8.8.16 Participant 16

ANNIKA 0:00

Thank you so much for taking the time to do this interview. To start with, what was your general impression of the exhibit you were presented with today?

PARTICIPANT 16 0:08

I thought it was very cool, really interactive. I feel like I'm really a museum goer. So, I think a lot of museum exhibits you are just meant to stand and look at. But I think it's really good that you first have to build something and then move it around. And especially, I thought it was really impactful to like- when you place it on the one of the sister that was missing, it was like the bit about her and so on. So I think it relates the information to what you're doing, so it's more like tactile. It was good.

ANNIKA 0:38

And then on a scale of one to five, with five being excellent, how would you rate your enjoyment of this exhibit?

PARTICIPANT 16 0:44

I think five. I thought it was great.

ANNIKA 0:47

How engaging and interesting did you find the learning experience about the statue's history?

PARTICIPANT 16 0:53

Yeah, I guess I'm really the worst person to ask because I just love history and museums and so on, so I'm biased. But yeah, that was good. As I said, it really connects what you're doing to what you're hearing and what you're reading and so on. So you remember it a lot better. Yeah, so I think it obviously depends on people's learning styles and so on. But I think that generally it's as you do something, it makes you remember the story.

ANNIKA 1:20

And do you learn anything you didn't previously know about ancient Greece?

PARTICIPANT 16 1:27

I knew about the sisters, but I didn't know, like, for example, how they were posed and where exactly they were and so on. I just knew generally about them. So it was good to hear about them in more detail.

ANNIKA 1:42

Did this experience make you more likely to visit an exhibit that has a similar type of interactive piece in it?

PARTICIPANT 16 1:51

Yeah, for sure.

ANNIKA 1:53

Did the puzzle interaction feel like a meaningful way to learn or was it a distraction from the information?

PARTICIPANT 16 2:00

I think a meaningful way to learn, I would say but again I think it would depend on the person like for example I would worry maybe like kids or something like that might just build it and be like "yay" and then they would sort of be done and then move on and so on. I think especially as well for museums particularly when you have a lot of kids and so on when you build something a lot of people leave it built and then that takes out obviously a massive part of the exhibition when it's already done and you just put it there so that's the only thing I would say but I mean, I think it was good. I enjoyed it.

ANNIKA 2:39

Compared to reading a standard museum sign, did you feel like this was a more effective way to learn?

PARTICIPANT 16 2:47

Yes, I think so. Yeah, again, I think it depends on the person which way you absorb information the best. But yeah, again, the sort of tactile and listening and so on, I think it's a good way to remember.

ANNIKA 3:01
What was the most interesting thing you looked at, did, read or listened to?

PARTICIPANT 16 3:07
In terms of information or just generally?

ANNIKA 3:09
Generally.

PARTICIPANT 16 3:10
I think it's so cool that it connects. Where you put it, it starts talking to you. I think that's really cool.

ANNIKA 3:18
And now on the usability part of things, when you walked up to it, was the purpose of the replica clear? So did you know what you had to do?

PARTICIPANT 16 3:27
I think so, yeah. I think- I mean, with the- how it says, you know, touch me, I guess, yeah, I think so. I mean, I did it, you know, so when I saw it, I was like, okay, so I have to build this and then I have to put it there. Yeah. Yeah.

ANNIKA 3:42
Okay. And then on a scale of one to five, with five being very easy, how intuitive was the assembly of the statue?

PARTICIPANT 16 3:50
I think 5. I mean, I did it in the end. Obviously, I messed up a little bit, but I think it's pretty clear enough, I would say, yeah.

ANNIKA 4:03

And did the game aspect help you focus on the information or feel like a distraction?

PARTICIPANT 16 4:12

I think focused, I would say. Although because I was a bit worried, like, "Oh, am I doing this in the right order" sort of way? That was the only thing I was like, "Oh, maybe it won't make sense." Obviously when it's written down, it's chronological, right? It's like this bit is supposed to follow this. However, whenever I did it, I did it obviously the wrong way. And then the information kind of came out. It still is the same information and still makes sense and so on. But yeah, the chronology is a bit [...]

ANNIKA 4:44

Yeah, that's the way I've written the script. It's essentially that the clips still make sense. Because having a certain way that people need to do it is such a usability issue. And I don't want them to get discouraged because all of a sudden the pieces don't make sense.

PARTICIPANT 16 5:01

Yeah, and you're like, what is happening?

ANNIKA 5:02

Obviously, if you have it written down somewhere, there needs to be chronological order to it. So it's like a 50-50 way of it. And on a scale of one to five, with five being excellent, how did the material and the weight of the statue feel to you?

PARTICIPANT 16 5:17

I think five, because it wasn't too heavy. I don't think anyone of any age would have difficulty in picking it up or anything so I would say five.

ANNIKA 5:24

Did the visual and auditory feedback you receive feel immediate and logical after placing the assembled statue?

PARTICIPANT 16 5:30

Yes, for sure.

ANNIKA 5:32

Was there anything about the physical interaction that was confusing or felt like it could break?

PARTICIPANT 16 5:38

I don't think so, no. Because the magnets were very tight together so- I think no I didn't feel that.

ANNIKA 5:46

And you already touched on this but do you think this type of exhibit would be suitable for all ages? You already mentioned children but maybe considering the older generation.

PARTICIPANT 16 5:59

I would assume so. I guess the only thing is- I mean, I don't know. I guess it depends on what they've experienced before and so on is really the big thing and what knowledge they have of start here and continue. You know, that's the only thing. It's like, yeah, keep going. I think it would be pretty clear. Plus, like, maybe this is totally unrelated, but I feel like usually museums have like a person in every room that you could ask and be like, "Oh, so what do I- how do I use it?" So whatever. So I don't think it would be an issue.

ANNIKA 6:40

And lastly, do you have any suggestions for improving the way the information and the replica were presented? And is there anything you would do differently next time?

PARTICIPANT 16 6:58

Maybe just a sign to even make it even clearer that you put the statue on each thing, maybe. So that kind of negates the issue of all people being like, "Well, what do I do now?" So I think that's the only thing. I think it's really clear, like the signage and that you're able to touch things and the start here and so on. I think it's pretty clear.

ANNIKA 7:19

Perfect. That concludes our interview. Do you have anything else to add?

PARTICIPANT 16 7:25

I don't think so. No.

ANNIKA 7:26

Perfect. Thank you so much.

8.8.17 Participant 17

ANNIKA 0:01

Thank you for taking the time to do my interview. To start with, what was your general impression of the exhibit you were presented with today?

PARTICIPANT 17 0:10

It was amazing, the work put into it. There's a story behind what you've tried to show in there. However, I found the exhibit a bit passive so if there was an interaction option I would have much preferred that because it makes the learning way more interesting because it is a very interesting topic that's being discussed so I would like that to be- like to be able to play around with that just to learn.

ANNIKA 0:57

And then on a scale of 1 to 5, so with 5 being excellent, how would you rate the enjoyment of the passive exhibit you were presented with?

PARTICIPANT 17 1:09

3, I would say it was a regular museum experience.

ANNIKA 1:13

And how engaging did you find the learning experience, so learning about the statue in that way?

PARTICIPANT 17 1:21

Three as well. It wasn't very engaging as you were just reading a sign..

ANNIKA 1:23

And did you learn something you previously didn't know about the ancient Greece?

PARTICIPANT 17 1:28

Yeah, I did.

ANNIKA 1:30

That's lovely. And then, does this experience make you more likely to visit another exhibit that was structured in the same way?

PARTICIPANT 17 1:39

Not really, because I think most of the museums are set up in the same way anyway, so-

ANNIKA 1:46

Yeah, would it have made you more likely to visit an exhibit like the interactive one?

PARTICIPANT 17 1:53

Yes, yes. I would have loved that.

ANNIKA 1:56

And if you were presented with the interactive experience, so that allows you to touch the replica, offers you different information outputs, you already touched on this, but would you have enjoyed the exhibit more, the information more, or would it have been a distraction?

PARTICIPANT 17 2:12

Yeah, the interaction one definitely would have been better.

ANNIKA 2:15

And then, last question, do you think you would have learned more or would have been able to recall the information that was presented to you longer?

PARTICIPANT 17 2:23

Yeah, because I'd say there's more sensory things being involved in the- you're touching and, like, you're- you're listening to the audio whilst you're given the option of reading as well. So it just sticks around and like, it just helps you learn more.

ANNIKA 2:43

Yeah, that is it. Thank you so much. Do you have anything else to add before we conclude this interview?

PARTICIPANT 17 2:49

No, I have nothing.

ANNIKA 2:51

Thank you so much.

8.8.18 Participant 18

ANNIKA 0:00

Thank you so much for taking the time to do my interview today. To start with, what is your general impression of the exhibit you were presented with today?

PARTICIPANT 18 0:09

I think it was nice. A bit- I don't really like to read too much, so I think that's the part that I didn't like. Just having to go through a lot of it. I think it's a lot of information. But other than that, I think it was nice just to look at.

ANNIKA 0:29

And if you would have to rate your enjoyment of this exhibit from one to five, with five being excellent, what number would you put on it?

PARTICIPANT 18 0:39

I would say three. So more or less just a bit neutral about it.

ANNIKA 0:45

And how engaging or interesting did you find the learning experience in regards to the statue's history?

PARTICIPANT 18 0:53
I think that was good because there is a lot of information there. Even though it's a bit of a writing, but there is enough information to know the most vital things about it. So I think that was done well.

ANNIKA 1:08
And did you learn anything you previously didn't know about ancient Greece?

PARTICIPANT 18 1:13
Well, I don't really know much of ancient Greece, so I learned everything there.

ANNIKA 1:20
And does this exhibit make you more likely to visit an exhibit that would kind of be the same?

PARTICIPANT 18 1:31
Well, I think I just- in general, if I went to a museum, it would just be to look at what's there rather than read a lot. Because I don't find that very engaging. But just to look. So I think it wouldn't really make much of a difference.

ANNIKA 1:50
And if you were presented with an interactive one, would that make you more likely to go to a museum if you knew they had something like that?

PARTICIPANT 18 2:00
I think so, because it's a different kind of environment that I haven't been used to. Because in museums that we typically see, they're all just the other exhibit. The passive one. So I think the interactive one would be a different kind of way to interact with it. And I find that more engaging too.

ANNIKA 2:21

Okay. And that kind of goes hand in to hand what you already said, but if you were presented with this interactive museum experience where you can touch something, you have different outputs of information, would you have enjoyed that more or do you think it would have been a distraction?

PARTICIPANT 18 2:39

No, I think I would have enjoyed that more. I remember going to this one museum in Limerick and they also had some figurines and when there's light on them and they talk and things. I think that was more interesting, just like this exhibit, because you get to- you have, like you said, different senses involved. You're making it, seeing it, hearing it. And I think when you have all of those components, that's a better way to keep information in. Because just reading, at least for me, I don't read a lot like that. And I think history can be a bit hard to remember just by reading. So when you have that kind of an environment, it's easier to remember.

ANNIKA 3:21

So then you would say that if you would have had the interactive experience, you would have been able to learn more or would have been able to recall the information for longer?

PARTICIPANT 18 3:32

Yes, definitely. Because even when you're just looking at the statues, you're just looking, you might not remember, but when you're building it, you're kind of feeling different components of it. So even those little things that you can remember exactly what it looked like. Because I think in the quiz that I did, there was some question about, I don't know, their structure. I think I would have remembered it a bit more if I had touched it, because I didn't get to touch the other passive exhibit.

ANNIKA 4:02

Okay, that's already it with the interview. Do you have anything else to add before we conclude?

PARTICIPANT 18 4:09

No, not much, but I really enjoyed the experience, getting both the experiences, I think. They're really cool.

ANNIKA 4:16

Thank you.

8.8.19 Participant 19

ANNIKA 0:02

Thank you for taking the time to do this interview To start with, what is your general impression of the exhibit you were presented with today?

PARTICIPANT 19 0:09

I thought it was very interesting. It was nice to see that there was an empty space for the empty figure. I thought it was very interesting. It's a part of history I never [...] gotten into so it was nice to learn something new. So yeah, it was very interesting.

ANNIKA 0:28

And on a scale of one to five, with five being excellent, how would you rate your enjoyment of this exhibit?

PARTICIPANT 19 0:36

Enjoyment is a bit difficult with something passive, I think. It was very interesting, so I did enjoy it. I did enjoy learning something new that I didn't have any access to before. But yeah, I've seen the other version of the exhibit, which I think would be much more enjoyable for people, or for myself at least. So I would probably rate the normal one about a 3.

ANNIKA 1:04

And how- so you already said that you did find it engaging, interesting, because the history was interesting to you- so, if you're concentrating on the learning experience alone, how engaging and interesting did you find that?

PARTICIPANT 19 1:23

I wouldn't say it was very engaging because you look at it and obviously you can get a lot of information. And you can read it, but I find that you retain information much more easily when

you hear things or when you do something active with them. So it wasn't very engaging, I would say.

ANNIKA 1:42
And even though it wasn't the most engaging learning experience, did you still learn something you previously didn't know about ancient Greece?

PARTICIPANT 19 1:50
Absolutely, I didn't really know anything about these figures. I've seen pictures of them before, but I didn't even know their name or what their history was, or even that there was one missing, so I learned a new thing.

ANNIKA 2:04
And does this experience, so this passive experience, make you more likely to visit an exhibit that is similarly structured?

PARTICIPANT 19 2:15
I wouldn't say it makes me more likely. I enjoy going to museums anyway, so it's not really something that needs to be- Kind of the same. Yeah, it's still pretty much the same.

ANNIKA 2:27
And if there was an exhibit like the interactive one you saw, would these types of exhibits make you more likely to go to certain museums?

PARTICIPANT 19 2:39
Absolutely. If I knew that there was some engaging things in the museum, I would probably much more likely go.

ANNIKA 2:46
And if you were presented

ANNIKA 2:51

with the interactive museum experience that allows you to touch the replica of a statue, offer different information outputs such as video and audio in addition to text, would you have enjoyed that more or do you think that would have been a distraction from the information?

PARTICIPANT 19 3:07
I don't think it would be a distraction. I don't think it would be any negative experience at all. I think it would be a very positive point, actually.

ANNIKA 3:27
Lovely. And as the last question, do you think you would have learned more or would have been able to recall the information better if you were presented with the interactive one?

PARTICIPANT 19 3:36
Absolutely. It's more easy to learn that way.

ANNIKA 3:40
Amazing. Thank you so much for doing this interview. Do you have anything else to add before we conclude?

PARTICIPANT 19 3:46
No, it was very lovely. Thank you.

ANNIKA 3:48
Thank you.

8.8.20 Participant 20

ANNIKA 0:00
Hello and thank you for doing my interview. The purpose of my interview is to evaluate the prototype's enjoyment and usability. There's no risk associated and your personal information or any identifying information will not be included in the report. Your participation is voluntary and you have the right to withdraw at any time. Thank you again. To start with, what was your general impression of the exhibit you were presented with today?

PARTICIPANT 20 0:28

I thought it was very well made, in particular the pieces that needed to be assembled to form the statue. I thought they had a very high level of quality finish.

ANNIKA 0:42

Thank you. And if you were to rate the enjoyment of this exhibit on a scale of one to five, with five being excellent, what number would you associate with it and why?

PARTICIPANT 20 0:55

So I don't see it as an enjoyment experience. In this situation, I'd see it more as an education experience. So I'd probably put it at three for enjoyment.

ANNIKA 1:06

And in particular about the learning experience- you kind of already mention this- how engaging or interesting did you find this as a learning experience about the statue's history?

PARTICIPANT 20 1:26

I thought it was very innovative and come compelling, the way that it had you engage physically as well as mentally with the information and gathering the information, I think helped me to be more interested in it, be more interested in the history because I had something tangible in my hands, it helped link my body to brain.

ANNIKA 1:53

So would you say you've learned something during this experience that you previously didn't know about ancient Greece?

PARTICIPANT 20 2:01

Definitely, yes. Emphatically, I would say that I have learned something. I've learned a few things that I would not have been aware of and things that I would not have come across in other situations.

ANNIKA 2:13

Did you feel like that the puzzle interaction felt like a meaningful way to learn or was it a distraction from the information that you were presented with?

PARTICIPANT 20 2:22
I think it helped my brain context switch from previous things that I was doing outside of this user test. So it helped me engage more with the activity that was here and to prepare me to take in information.

ANNIKA 2:40
And compared to reading a standard museum information sign, did this feel like a more engaging and effective way to learn?

PARTICIPANT 20 2:47
Emphatically, yes.

ANNIKA 2:50
That is what I would like to hear.

PARTICIPANT 20 2:53
[laughing]

ANNIKA 2:53
And what was the most interesting thing you looked at, did, read or listened to?

PARTICIPANT 20 3:00
Given my background, the most interesting thing was the design of the overall interface. So not so much the historical aspects, but seeing how the object was put together, the other components like the screen, how the screen responded when you did different things. The statue itself, assembling the statue and taking the statue apart. So it's probably more the physical interaction element than the actual historical elements or the educational elements were the most interesting to me.

ANNIKA 3:37

Does this experience make you more likely to visit an exhibit in a museum that has a similar kind of setup? So if you were going to a new country and you were looking at museums, would you choose a museum that has a similar interactive piece over one that might not?

PARTICIPANT 20 3:54

It's probably not one of the criteria I look at when I choose to go to a museum, but it would be something that would make me remember going to a museum or having a museum experience over a standard museum experience that doesn't have this sort of digital interaction element.

ANNIKA 4:11

That was everything on engagement and enjoyment. So we're going to move on to usability and experience. Was the purpose of the replica clear before you started?

PARTICIPANT 20 4:23

Assuming that the purpose is education, I think so, yes. If it's something else, then no [laughing].

ANNIKA 4:32

And then on a scale of one to five, with five being very easy, how intuitive was the statue to assemble?

PARTICIPANT 20 4:40

The statue specifically. I would say pretty easy. It would be four or five. Maybe five because I think the little magnets helped you figure out where to align things on top of everything else. So five.

ANNIKA 4:56

And did the game aspect of the statue help you focus on the history that came afterwards or feel like a distraction?

PARTICIPANT 20 5:04

What was the game element?

ANNIKA 5:06

So the game element is the puzzle of the statue. That is designed as a puzzle.

PARTICIPANT 20 5:11

I didn't experience that as a game, but maybe it is. I suppose there's a challenge to it. Okay. Ask me the question again, sorry.

ANNIKA 5:24

Did the game aspect help you focus on the history or did it feel like a distraction?

PARTICIPANT 20 5:29

I think it helped me get my mind in tune with the activity that was going to follow. So, yes, it helped me focus.

ANNIKA 5:38

And on a scale of one to five, with five being excellent, how did the material and the weight of the statue feel to you?

PARTICIPANT 20 5:46

Five. Excellent. Yeah, it was really good quality. The quality of the print is noticeably better than I've seen in other places. And yeah, again, I'm jealous.

ANNIKA 5:57

Did the visual and auditory feedback you received feel logical after placing the assembled puzzle on the base?

PARTICIPANT 20 6:06

When it didn't work it wasn't clear why it wasn't working and the presence of the plant and it defaulting back to the plant when the sound finished I had to learn over time that that was a thing. So it was more of an over time pattern recognition. So that wasn't intuitive. But the rest of it, yes, was fairly intuitive.

ANNIKA 6:30

Yeah, there's a little bit of a disconnect sometimes between someone looking at the screen and looking at the base. Because if you look at the base, the base gives you an immediate feedback if it's placed right or not. Because the light will only turn green if the statue is placed correctly. But if people are concentrated on the screen, they miss it. The placement of the screen is very dependent on if it is in eyesight or not. The original idea with the spotlight was- There needed to be enough movement with the spotlight that you notice it if you're not looking at the screen from the beginning but not enough that it distracts you from the information. So it was a really- very intricate play of balance. Something I learned from the user test was that the way this screen is placed is not ideal.

PARTICIPANT 20 7:54

I think it could benefit from having- so that light signal that you have on the box, given that most people's eyes are attracted to screens, unfortunately and there's loads of research behind that, it would be good to have a visual indicator on the screen duplicating the visual indicator on the box to show whether something is placed or not.

ANNIKA 8:14

Would you do that in the sense of a light maybe in one of the corners as well or as text that is kind of just popping up like an error message almost?

PARTICIPANT 20 8:23

I think it would almost be like some sort of a prompt to tell you to place something. So maybe it's text because I only see text but it could be something else. So if it was text something like "Please place the statue on a plinth".

ANNIKA 8:41

So almost like this is a little bit grayed out and then you have a text over it and that gives you kind of a prompt-

PARTICIPANT 20 8:48

A prompt to do something, yeah.

ANNIKA 8:50

Okay, and then it disappears obviously once you replace it.

PARTICIPANT 20 8:53

I mean you've done the visuals that you've done here are much better than that suggestion so probably if you went away and thought about it you come up with something better than text. But even if it was a blue light on the.- oh sorry, a green light that showed red or something to indicate.

ANNIKA 9:10

Yeah, just something that kind of connects the screen with the base interface.

PARTICIPANT 20 9:14

To tell you that there's something you need to do.

ANNIKA 9:16

That's a really good idea. Was there anything about the physical interaction that was confusing or felt like it could break?

PARTICIPANT 20 9:27

When it didn't work for that first placement and the purpose of the plant. So I think I've already touched on this. But otherwise it was pretty good, I should say. This is niggly, I'm being niggly. It was very, very good.

ANNIKA 9:47

Do you think this type of exhibit would be suitable for all ages in a museum?

PARTICIPANT 20 9:55

I think it's probably too- so young children would have trouble with dexterity to something of this level. They probably need larger pieces. But I think the concept could be duplicated to work for them.

ANNIKA 10:10

And the older generation that might-

PARTICIPANT 20 10:15
Have arthritis? I think you could work with that with arthritis. So my mother has arthritis. This isn't the kind of thing that she would have trouble with.

ANNIKA 10:23
Okay, and then for our last question, do you have any suggestions for improving the way the information and the replica were presented? And is there anything you would do differently next time?

PARTICIPANT 20 10:36
I think I've already touched on the do differentlys. I think it's really good quality. The only thing that's letting it down is your little cardboard box [the box the statue pieces are located in].

ANNIKA 10:44
I ran out of my printing material.

PARTICIPANT 20 10:47
It doesn't match the same quality. Everything else you've got has really high quality. So I probably guess it's very niggly. I'd redo the box. I love how your text is done. This is really good. I'm totally going to steal that.

ANNIKA 11:02
That's the end of our interview. Thank you so much. Do you have anything else to add before we conclude this interview?

PARTICIPANT 20 11:08
I just think it's a really exceptional idea. I think it's really innovative what you've done. I hope you're very proud of yourself for it.

ANNIKA 11:16
Thank you so much.

8.9 Expert Interview Questions

Learning:

1. What do you think are the biggest challenges in creating interactive and memorable learning experiences in museums?
2. Do you think elements of Game-Based Learning improve engagement with cultural content?
3. What do you think about the usage of NFCs for interactive replicas?
4. What has your experience been with NFCs in “seeing without sight”?
5. In your opinion, what modality provides the most effective learning experience (audio narration, visuals such as animations and/or text)?

Integration:

1. From a maintenance perspective, is the ease and low cost of replacement when using PLA more important than the higher realism and detail a more expensive material would offer?
2. What kind of staff training, if any, is needed when exhibiting interactive and technology-enhanced replicas?
3. What are the hunt museums' capabilities for maintaining/repairing electronics such as Arduinos and NFC readers?
4. What is a realistic budget for the per-unit cost of a display item in the hunt museum when considering long-term integration?
5. What are the safety concerns when exhibiting interactive and technology-enhanced replicas?
6. Is a 3D-printed replica, constructed as a puzzle, durable and sustainable for long-term museum integration?

8.10 Expert Interview Transcript

Annika 0:00

Can you state your name, please?

Maria 0:02

Yes. My name is Maria Cagney, and I'm curator of education and outreach here at the Hunt Museum.

Annika 0:08

Perfect. And do I have your consent to record this interview?

Maria 0:12

You do.

Annika 0:12

Perfect. Okay, then we can start. So, my first question would be, what do you think are the biggest challenges in creating interactive and memorable learning experiences in museums?

Maria 0:28

I suppose, firstly, it is probably the need to educate staff more on what these terms can mean and what they can be in reality. So for specialists working in the field, game designers, they know about what's possible, but for us who work specifically education and work in community as well, I'm not a game designer, so someone needs to sit me down and give me examples of what's already happening in that world, so I can start to wrap my head around possibilities here, and that applies to everyone here in the museum, not just me. Cost, to bring in the expertise, is significant as well. Any of the interactives, whether we're talking about the digital table in the PROLOG room or the sensory station from 'Seeing without sight', they were part of funded projects, so we had to go out there and get the funding for those interactives. Cost also to maintain the interactives. When we want to... the framework for the digital table, it's more or less in place. Maintenance costs are what's significant there. We can build and add collections to that framework, but it regularly needs maintenance of breakdown and even in other museums where I've worked in Northern Ireland, interactives and galleries like we had SLAs with all the companies, but they regularly broke down. So those agreements were really, really necessary. In terms of more analog approaches then to interactive such as the 'seeing without sight' one upstairs in the PROLOG room, it's a lot more low maintenance. The problem with that is, as you know, Annika, we have 3d models with NFC tags, and the NFC tag is located

on the bottom of the 3d printed object. So when it's placed on the museum in a box device which reads the NFC, sometimes the boxes don't work. Pieces, sound cards, things like that within the box, they get exhausted. Those boxes aren't expensive to buy, but again, internal knowledge and experience in regards to fixing those devices. We have a little bit of it internally. Some staff have showed initiative and have learned how to fix basic things that go wrong with the boxes. They also have a limited life span.

Annika 3:15

That's one of my problems now in developing the electronics that the cables actually break, so often that I have now big box of cables that I have to replace almost like every couple of days, because I'm currently developing it so heavily that they just break after a certain amount of times of being used.

Maria 3:34

Yeah, yeah, yeah. And even while we're talking about this, we have an app which was designed by a group of students from Trinity called Musa, and it is designed specifically for people who are deaf. And there's a series of sign language based tours highlighting particular collections, but when you're in the museum, you have to scan QR codes to access that content, and in the last week, we've had big problems with the QR codes. And temporary ones have been issued, but a permanent solution has not been found, and to spend the time... those codes were initially commercially printed, we don't have the budget to replace them, and so in the meantime, they're not working. You know, it's now in their case, they got kicked off the Trinity server, but never told us. So next thing we knew, the QR codes weren't working. But a solution as to where that content will sit. We're trying to find the solution right now.

Annika 4:46

That's a big problem with QR codes, where people generate them on a free website, it's up and running, and then two months later, oh, no, you have to pay and that's all gone.

Maria 4:54

That's it, and that has to be avoided, certainly in an environment like this. You know, we're trying to provide the best customer and visitor experience we can. So basically, things like that don't work.

Annika 5:08

And it doesn't create a good experience, if you go as a visitor to a museum and you're excited about this exhibit and then it doesn't work.

Maria 5:16

Oh yeah, yeah,

Annika 5:17

You're going away from a museum with such a bad like, kind mood

Maria 5:21

-expression of the museum that we don't care and that's exactly what we're trying to avoid. Yeah.

Annika 5:29

Then my next question is, do you think elements of game-based learning improves engagement with cultural content? So, game-based learning in the sense of your... it's like the puzzle idea that I have in my project which is considered a game so that you have a little bit more of an interaction, you add a games aspect to it. Would that help improve it. Or do you think that would confuse visitors more?

Maria 5:53

No, I think it's a really, really good thing. And I think any way to incentivize learning is great thing, even in my limited experience of game design, we would always try to incentivize learning. So I mentioned I do a lot with schools, and we have had collaborations with students in other colleges to design the odd game, and that point-based opportunity to gain points and learn along the way. It works really, really well.

Annika 6:23

That's very good for my project.

Maria 6:28

Anything like, there's been such a kind of return to, you know, tabletop games. We have wonderful collection of of game pieces in the collection. And for a long time, we've been trying to find ways to create gaming experiences using these, you know, 3d prints of them, nice, nice, high quality replica, 3d printed. And even the chessboard outside like that's the simplest example how well game based learning works in the museum. There had been plans, and we may return to it again in the future. Funding was, was the problem to actually have replicas from the collection on the tops of the game pieces. So we did a big piece at the time, there was plans. We were heavily, very heavily involved in a proposal for a Gaming Museum in Limerick at that time, it was to our previous director, Jill Cousins, who could be an interesting person for you to talk to. Yeah, she's very big in gaming and any way to encourage playfulness in an environment like this, like should, should be looked at seriously. You know,

Annika 7:51

Yeah, I agree. We had, I was in Waterford recently, and they have the Reginald's tower, which is just the tower that was used as a defence and later as a prison. If you go in, there's not much in there, not that interesting. But they recreated little cut outs where prisoners would play games out of like handmade, like little wooden pieces. And they had replicas of these games there, and you could just sit down in the tower and play bridge, and all of a sudden, instead of going in, going up and going down in 10 minutes, you spent half an hour, and you actually remember what you, even if it didn't have to do anything with the actual game, you remember things you did just before and just

Maria 8:30

Yeah.

Annika 8:31

way better.

Maria 8:32

Yeah, yeah.

Annika 8:34

Then third one is, what do you think about the usage of NFC tags for interactive replicas. And can you connect that to maybe the exhibit you have upstairs where you're using NFCs?

Maria 8:46

Yeah, we've had very positive experience overall with NFCs. I mentioned the museum in a box device that we use, so we have to use NFC tags in conjunction with that. The issue has not been with the NFCs. It's been with the boxes. But there's a really nice... the museum in a box when you buy one, you have to set up an account, upload your files to the cloud, the account, and, you know, we in the past, would have had multiple boxes on the go with different files, and you can use files interchangeably on different boxes, apart from the bits I mentioned about the box physically stopped from working. The NFCs have been very much no problems at all. When someone like me can program the boxes on everything, the cards I forgot. I forget how it works, but overall, it's been very positive.

Annika 9:44

But that's good that you can forget how it works, but you still can work with it. That's the kind of idea. Obviously, I'm doing it from scratch now to kind of show that I have the ability to create something like that, but in an ideal world, I'd create a kit that is then as easily programmable for someone with no experience, as someone with experience, and you got a repair kit that has everything in it, and ideally would be in a box like that where you can access what you need, but everything else kind of cut off so you can't accidentally do something that you're not meant to.

Maria 10:15

Yeah, yeah. And I did explore the idea of us making our own boxes with Fab Lab. Have done a good lot with Fab Lab and over the years. And it was, it wasn't that the cost was the issue of buying the box, but we rather it was to try and overcome some of the issues with the boxes, actually, so that we'd have more control over that. We've prepared them ourselves. So again, budget, but it's something I still want to return to, and maybe we could do through your work. Yeah, you know.

Annika 10:53

Because that's like, currently what my work is, I'll have a 3d printed base that works as a box, but all the electronics, you can essentially lift the lid off where the model would sit on top, and you can see all the electronics, because currently I'm experimenting how do I position them so I can still access them. Because I do, I don't use the most expensive material, because for one, I want to see how cheap can you go getting something good out of it. But also, I have a very limited budget, because it is an FYP and not a master thesis, and it's has been creating a bit of issues that, if I design it in a way that I can't access all the components, the risk of something going wrong on the Showcase day, and I go, I can't do anything, just too high. So it needs to be designed in a way that I can access everything in a second.

Maria 11:46

yeah, yeah. It's access, isn't it? But these are all considerable, you know, things for consideration. This environment as well, for sure. There is a museum in a box. I don't know if you've looked up the website, but there is a WhatsApp group that Emma, a colleague of mine in education, when she needs help with repair or trying to figure out what's wrong. There's been great support through that Whatsapp group. So that's the guy. I need to look up his name. He's really thrilled what we have done with Museum in a box here. I get emails quite often, people just wanting to know more. But he feeds into that. But other museums who have the boxes also give advice and guidance to her.

Annika 12:44

It's a handy thing to have a community like that. I only found out about it when I was looking at it upstairs, at the actual exhibition, I hadn't heard of it before, and then I looked into it more and was like, this is actually genius to make what I'm currently making from scratch a little bit easier, like if I had this idea, but I wasn't an interaction designer, you can know who has a little bit of knowledge in programming and electronics that would have been ideal to use as well.

Maria 13:15

Yeah, yeah, yeah, yeah. They're based in the UK, so we've had to send boxes over there for repair and pay customs and customs on parts and stuff like that. So it's not, there's a lot good about it, but there's some challenges as well. Yeah, those boxes are very popular in museums. The British Museum use them, I know some of my colleagues in the north in museums in Northern Ireland use them. They're a great way to go.

Annika 13:47

They're probably one of the only ways of doing it like that. They've really created a very good business idea and a niche kind of when no one else explores it before.

Maria 13:55

But they are working in very small scale. They do drops of boxes, and then look on, and you have to wait some months until they get the parts back in stock. And is there a Raspberry Pi component within that? You know, I forgot.

Annika 14:11

I think so. I'm using, I think I looked into it, and I'm using an Arduino, and they're using the Raspberry Pi, because with the Arduino, I need to connect it to a computer, whereas the Raspberry Pi can run by itself, but it's also a lot more complicated than the Arduino would be.

Maria 14:28

Well, there was a time it must have been shortly after covid where Raspberry Pi's were really hard to get and their boxes were just every time I checked, still out of stock, still out of stock, and it's gas how global situations can impact things like this.

Annika 14:49

It's one of the things that I had to justify. There's a whole section in my report that says why I'm using Arduinos over Raspberry Pi's. For me, that just made more sense. And that setting, if probably do ever do this on a big scale, Raspberry Pi, does make more sense, because I can do more, with still being the same size

Maria 15:10

yeah, and work independently.

Annika 15:12

Exactly but for what I'm doing now, where I will always be next to the exhibition in that sense an Arduino just work better, yeah, but cheaper as well. Then, the fourth one, in your opinion,

what modality provides the most effective learning experience? So audio narration, a visual or maybe just text or combination.

Maria 15:36

I think it's definitely a combination without question. We all learn in very different ways. So giving people option, giving people options is really, really important. And I spoke to you before I think about the sensory trails and trying to get funding for it so that, well, it's designed with the neurodivergent community in mind. Will... we have work done on what objects would be included. But the idea is that people would, can engage with a handful of objects and go as deeply as they like into terms, in terms of building their knowledge and exploring that object, but giving them a game based option, an audio option, a physical option, where they can make something in response to the object. So and touch obviously been the tactile been really important as well, and the audio. So for an artwork, you know, a slow art, someone guiding them through a slow art activity, something to touch. It might just be what it feels. You know, there's some of the paintings in the collection are very, very heavy with very heavy layers of paint that they can touch, something like that. And and then the Doom might be that they create something artwork wise. And keep very simple, yeah, a combination, for sure.

Annika 15:36

I saw, I don't know which museum did it, but it was rugs and other textile that they had. And like with textile, I always want to touch it, but obviously you can't, because you know you're going to damage the artifact. And then for later generation, they might not have it, because you've now got the opportunity to touch it.

Maria 16:48

You, and how many other people touching it?

Annika 16:50

So what they did was they, the historians, created a replica of that texture, and then did a little cut out next to the text, and were like, feel free to touch this, and then you can still touch it without the actual artifact being in danger of being damaged, which I thought was a really good idea.

Maria 17:43

We have done here for 'seeing without sight'. There's with a lovely collection by the designer, Sybil Connolly. So designs, beautiful dresses and skirts, all she would have used traditional Irish materials, linen, wool. She's famous for pleated linen. So to make one yard linen, she needed to use the raw materials of eight yards of the unprocessed linen, right? So eight yards of that to make one of the pleated linen. So it's, it wasn't, it's her signature is pleated linen, right? And we had one of the objects in that exhibition was in the ket for a dress, a beautiful white dress with pleated linen. So obviously the object was in the case. But to give something tactile, so you could feel the ethereal kind of quality of the linen I got, I found someone in the north in the linen museum who reproduced the pleated linen. I can find it for you before you go, and you can experience it. And it just, it just totally changed the whole experience of this makesh. And that was very, very bespoke work, you know, yeah, Connelly didn't bring it forward in in her work that she had a specialist in Belfast that used to produce the pleated linen for her, but it wasn't cost effective. So after a time, she didn't bring it forward, you know. But I suppose, as the years went on, and I suppose, yeah, linen, the linen industry in the north declined so much. Anyway, going off point, would you see what I mean? Yeah, absolutely tactile in every way that you can, not just with the 3d printing or whatever.

Annika 19:39

Yeah, that's kind of.. because I got, when I was talking to friends about it, they were like, oh, do you need all three modalities, because I'm planning to, the video is done by now, but I have the animation, which is kind of like a visual, kind of tries to grab your attention a little bit again, engages you in different way. Then you have the audio, where you can actually hear the text. But also I'm still going to do the little signage, which has the same text on it so you can read it, because me in particular, like I love having to see something, but if I just read it, it's going in there, out there, so having a combination of hearing it and seeing it, will be amazing. Like when I read a lot of the times, I'll have the audio book on while I read the book. I love that. But that's me, so I can't...

Maria 20:32

Well, my partner, who's exactly the same, he's dyslexic, and he finds that hugely helpful as well. Growing up, in a big way. He found it helpful students.

Annika 20:43

That's the only reason I could read Shakespeare. I tried just reading it. I was like, Okay, no, this is not gonna work. Okay. So now we're on the integration part questions. So the first one is, from a maintenance perspective, is the ease of low cost replacement. So as I was saying before the PLA that I'm using here, that material is fairly cost effective, but it's also not as durable and not maybe as precise as a resin would be. In a museum context, because you were mentioning budget a lot. What is your opinion on those two or more materials? Those using a PLA even though it might need to be, it's not as durable, but it is very cheap and easy to replace. Does that make more sense than using a resin, or is the high investment of a resin, where you have to pay a lot up front, but you might have to replace it less does that make more sense?

Maria 21:41

Yeah, I get what you're saying. I think both are needed. It depends on the object. It obviously depends on the budget, but we're, in order to be true, as true as we can and as authentic as we can to the object. And that, you know, we have to keep that in focus, central on all the time, the objects we have printed in PLA and for at different times we've printed in resin. The resin ones are more durable. They are more an investment. So it's, you know, it's on a per project basis here. So unfortunately, it does come back to the bottom line in terms of pensions and pence, but it also, yeah, it's part of the decision making has to be around the object as well. There's no good printing a really delicate object in PLA because the sensory experience, you know, it's not going to be memorable. Also, I think I'm doing a piece, I told you about Ty Charles, I'm doing the, he does an awful lot of work in access using 3d capture and really printing technologies and safety is a concern as well. So with the PLA the edges tend to be rougher. You know, with the resin, it's a smoother experience and maybe a safer one. I don't feel I answered that really well, Annika, it's just it depends. It's per project. We have to consider all these things that you know to me.

Annika 21:42

But that's a perfect answer for me.

Maria 22:28

I mean, there is no perfect solution. And we have to kind of think of the object as the starting point. And yeah, we want to give best experience, sensory experience, possible. Budget does come into it, you know?

Annika 22:44

But that is but a really good answer I can work with, because that's exactly what I've been working with so far. I can't afford resin at the minute. I don't have a resin printer. I don't, I can't afford it. I have a PLA printer because they are a lot cheaper. And I do have the Marble like PLA print filament to at least give it the illusion of looking it, but as soon as you touch it, that illusion is gone. It feels like plastic,

Maria 22:51

Yeah. And weight, weight wise everything.

Annika 22:51

It's very light. And one thing I'm looking into now is for one making it heavier by filling it with sand, making the infill a bit better. So, yeah, it gives a little bit more of a heaviness. But I also had to sand it down after I printed to give some of those edges like my print luckily, the way that it is designed is already a lot smoother than when you just print something normal, but there were still edges where I went over with sandpaper to just make sure that it's all good, because I did cut myself on my very first print. It was a bit of my fold as well, yeah, because of the way I was handling it. Yeah, I don't think a user, a visitor would ever do that with a 3d print, but that kind of showed me, okay, you actually do need to, with PLA, need to be careful with how you're treating it, because it can't have sharp edges or even if you have children interacting with it. You don't know what they might do. I don't know what a child would do with it, and they're most likely to get hurt properly with it.

Annika 23:17

Yeah, well, that's it and but we have had the 'seeing without sight' exhibition. Two objects have gotten broken. They were both PLA, I just sorry, sometimes get confused around after letters. And they've been clean breaks and but the edge is quite sharp, always with children. That doesn't put me off children, one day, these things are going to happen. Yeah, and so even when, so when they're intact and they can be sharp, but when they're broken, they can be

even sharper, you know, until discovered and taken away out the space. So that's maybe something to think about, and purpose of the engagement. So if I'm doing a program with students here, leaving cert students, and we are talking about, part of our conversation about a decorative object might be around, you know, shape and form, the volume of the object, or whatever. Maybe the textures don't need to be A1 for that, you know. But if I'm doing a piece and it's with visually impaired in mind, yeah, we want to get the text so that audience and those that are engaged in particular activities, so it's, you know, what are, where are they coming from? What are their needs?

Annika 24:26

No, I agree with that. Because if you'd be touching that, you'd immediately know it's not marble, but if you can see it, you can associate, okay, this is meant to be marble.

Maria 24:26

Yeah, yeah, yeah. It's the visual impact, like here, yeah.

Annika 24:26

Bit of a combination of deciding factors, yeah.

Maria 24:26

We weight is up with every project and every project is going to be different, yeah, I think, yeah.

Annika 24:26

And then you mentioned this before in the first question, but what kind of staff training, if any, is needed when exhibiting interactive and technology enhanced replica or interactions?

Maria 24:26

Staff training? So yes, with Museum in the box, thank God, we have Emma, our in house museum in a box engineer, and she gets her support through the WhatsApp group that I mentioned. We've had to send boxes away for repair at times as well. Then otherwise the framework, so Shan, we work with a company called no hope, a game design company. They have

done the most of our designes for interactives, for exhibitions and in our galleries, there. So very little training, if any, has been accessed from them or through them. But they have set up the framework for the big digital table. And Shan, who's quite good with technology, she's, I don't think she's ever had problems adding collections to that. It's just to get the time to kind of immerse herself in it. And so yeah, the training piece, there's definitely room for improvement there. Think some staff, including myself, are still quite scared of the technology that table still scares me.

Annika 28:24

Yeah? And especially if then the person that you have in house, for example, gets sick or goes on to maternity leave, if it's a woman...

Maria 28:33

another job happens all the time. So yeah, those skills walk out the door so it's not sustainable way to do working at all.

Annika 28:41

So if I'm understanding it right, a staff training would probably be preferred, that even if you have an in house person, that some other people that are working in that region would know what to do if something breaks.

Maria 28:52

Yeah, for sure. For sure.

Annika 30:02

Then what are the Hunt museums capabilities for maintaining and repairing electronics such as Arduinos or Raspberry Pis and NFC readers?

Maria 30:11

None really, apart from what I just said already. We're not technologists, we're not interactive designers. We're not... we're museum folks. Yeah, you know, my background is in fine art, and

Emma's is in fine art. Una's is in fashion and history, you name it. But none of us are coming from a technology background, although things are changing, I think.

Annika 30:38

So you're always relying on either external people or bringing people, hiring people for exactly that.

Maria 30:44

Absolutely. yeah, yeah, yeah.

Annika 30:46

Probably also not very sustainable, if you want to incorporate technology into museums long term.

Maria 30:51

yeah. I mean more. We're a small museum that needs to be said, but larger museums do have digital departments. So for digitisation, whether that's 3d capture or, you know, for that side of the house, you're going to have people more likely to have skills for maintenance of technology if you have a department like that. So, but we're so far behind the curve in Ireland, it's scary. Yeah, I mean, we started digitisation in this museum in 2018 and we're still leading on 3d digitisation. I'm talking about the Nationals haven't got up or anything. They don't really quite understand why it's a good thing to be doing.

Annika 31:35

Yeah, I've heavily relied on the Acropolis Museum having digitised their art because my video that I'm now doing, because, if you remember, I said, okay, I want to incorporate their original back into my replica, because there's no point in having that whole elaborate exhibition and then no one looks at the original.

Maria 31:57

Yeah, for sure, yeah.

Annika 31:59

But because, obviously, I'm not in Athens, I've made a video, so an animation of it that is on a video screen or a projector, and then something happens, and it's now a light spot. And in the original, if you were in the museum, you'd have a spotlight going on and off. Don't have that so its a video, and obviously I have 3d modelling skills, not to the extreme that I can replicate an ancient Greek statue, not a chance in hell. So I've been relying on their open source 3d scans of their models for this whole project. Otherwise, I would have had essentially stick figures probably instead. And it's such a great thing, not just for them to have it, but also for outside people like me who are interested in that type of work, coming from different perspectives, putting in a little bit of a creative twist on it.

Maria 32:57

Absolutely, reusing in your own way. Yeah, yeah.

Annika 33:00

Instrumental that there was the digitalisation that has happened a couple of years ago. It's amazing to see there's so much out there from the Acropolis Museum. It's great. One of the reasons why I chose it.

Maria 33:14

Absolutely, you wouldn't be doing a project on focusing on their collections, and they weren't out there.

Annika 33:22

Then like, yeah. Okay, maybe if I'd chosen something from the Hunt Museum, I could have actually done it here. But that was when I started, when I had that idea that was still up in the air where exactly I was going. So having that option of digitalisation is amazing.

Maria 33:37

It existed already. Well, we're wide open for collaboration here. Wide open. Tell Mark that. Remind Mark about that.

Annika 33:48

I'm actually seeing him tomorrow. But no, he was very delighted when I said this worked out. I was going back.

Maria 33:56

Yeah, good. You are always welcome here.

Annika 33:58

Thank you. Then where were we? Okay, what is a, now, this is going hand in hand, all of this, what is a realistic budget for the per unit cost of a display item?

Maria 34:11

I don't know if I can answer this. I remember when we were getting some of the first objects, 3d printed with Fab Lab. And I think there might have been six objects that were going back, probably tail end of covid, and some of them were resin. So, you know, the lead in time, the preparation, the trial prints, everything that has to be done to get that print that's right for display at the end. And I think the bill was about 2000 euros, but it was for maybe six objects, and Jere should have been charging more in Fab Lab, except we have great relationship, and we help each other out. So like at the time, that was considered a lot, I wouldn't be surprised, now that I know more about the costs, I wouldn't be surprised if I got an invoice for that, you know, for even four objects. Now, you know, we've been very lucky here. We do so much in partnership and collaboration, and even the inclusive museums project I have, and the 'seeing without sight' project, zero costs, because we partnered with confirmed smart manufacturing and who no longer sadly exist. Think I was telling you about them Annika. They didn't get their Phase Two funding and closed overnight, but they had industrial printers, and were more than happy to work with us on that project. So, huge social benefits to partnering with us and those prints, I mean, I can't imagine five, 6000 euros more, even, because they're so high quality.

Annika 36:04

Yeah, because when I was looking into it, I was really struggling. Because one of my questions is, how do I make it sustainable for long term integration, and that obviously budget comes in. It is a really big factor. If a museum can't afford it, and it doesn't matter if the British museum might afford it, because you want it to be accessible to a lot of people, that means including small museums as well as big ones. And when I was looking into it, I was trying to cap myself

at 100 euros for this whole thing, and because I already have knowledge that probably is possible, because I know quicker when a print fails. I know quicker what could make a print fail. But obviously that's me, yeah. So that means a museum would have to hire some sort of expert again, which would increase the price, because I'm not calculating my own labour costs. I'm just calculating the material costs.

Maria 37:04

Yeah, exactly.

Annika 37:05

So it was interesting to see, even if it's just an estimate, where that kind of plays around. So I'm not going like completely crazy with numbers, because I just have nothing to compare to. I've no clue.

Maria 37:20

I know, yeah, I'm not sure what I, what the information I've given to you there is useful. Again, our budget would be per project. So for 3d printing, for exhibitions, there'd be a budget line for that kind of thing. And, you know, 1000 euros might be put in there, but that might have to be increased. Yeah, you know, I mean, ways that we have reduced 3d printing costs is by working with the maker space in UL. [REDACTED until 39 minutes 36 seconds]

Annika 39:36

Okay, then you already mentioned safety concerns with these exhibits with the sharp edges on the PLA. Can you think of any other safety concerns when it comes to interactive...?

Maria 39:46

Yeah, it's something we talked... it's less about safety, and more, again, about access. We talked about it the last day, and how, how our interactives going to be made accessible. So the height that they are sitting at on a place or at a table. And it's something I had to think about with 'seeing without sight' and upstairs in that display, we used electric, electric tables that come up and down so that someone with a wheelchair, a wheelchair user can get their wheelchair in under the table, and they can comfortably, then interact with the objects at

whatever height they need. That was something that came, just struck me when, when, when I read that question. So less about safety, and...

Annika 40:37

That's actually a really good point with the height adjustable desk, because when we were talking about it earlier, and you were saying that to me, but I didn't even have to think about it, because wheelchair users, I think only when I came to UL I've met people in a wheelchair that wasn't kind of the group that I was surrounded with, so that obviously never really crossed my mind. Yeah, and now I have people who are sitting in wheelchairs, and there's completely new things where I'm thinking about I was like, oh, yeah, this door is heavy to open, yeah, but then I forget it again. Whereas a wheelchair user, one of my friends, she can't even use that door, she has to go around it unless someone opens it for her. It's things that you don't consider until you're confronted with it. So that was a really good comment, and height adjustable, because I was thinking, Oh, sitting down. I know a lot of people who don't like sitting down, so they would skip the exhibit because they have ADHD or something, and if they sit down, it's over, in that kind of sense. But at the same time, if you don't have that low then someone in the wheelchair or children might not be able to access it. So having a height adjustable desk is pretty...

Maria 41:47

That one there is quite adjustable. And there's yellow top ones in the 'seeing without sight' exhibition as well. So we use them quite a bit around here.

Annika 41:56

We have them in the library, not a lot. I think there's, I saw, like, maybe four. There's probably more in different places, but there should be even more than that.

Maria 42:06

Yeah, so many people have back problems and can't stay sitting for a long time, and that. We have some in the offices. Like, I don't have one. I wish you did.

Annika 42:16

I had one during my work placement, and it was amazing. Yeah, just even to like, if you feel like, what you need to move, even just lifting up the desk and having, been able to shake your legs out of it. yeah, stretch out, yeah, Or even then. But I also sometimes really wish that museums had more seating opportunities. So a height adjustable desk where you have maybe a chair adjacent to it can help all sorts of people.

Maria 42:49

Yeah, it's very, very true. And multi mobile stools as well. We have some of the accommodation station. And therefore, for this, people with mobility problems, just anyone wants to borrow. I always feel like you need to be in top health, such good health to be going off to somewhere a museum, even a museum as small as this. But you know, it's all the cabinets are full of objects. And I find while in love, and I find it quite draining, and I do need to take breaks. So you go to somewhere like the MET in New York, absolutely ginorm And yeah, and I find that really overwhelming. So breaks, regular breaks, is the secret. And seating and all that.

Annika 43:34

Yeah, I don't know which museum it was now, but I know that this one museum allowed us to go in on three days you paid once, but yeah, three days,

Maria 43:43

That's a good idea.

Annika 43:43

because it's so big that they said we'd rather have you come back another day than do it all in one go and then go back out of the museum, being overwhelmed and not actually enjoying the experience.

Maria 43:54

Or making for a memorable, memorable in the right way experience. Yeah, I find it quite overwhelming.

Annika 44:00

Yeah, okay. And then the last question I have is, is a 3d printed replica, constructed as a puzzle, durable and sustainable for long term museum integration? In your opinion, if I now fully develop this with your feedback, with user testing feedback, do you think that that would work in a museum environment, considering all of those factors?

Maria 44:32

Yeah, I think it's, it's a brilliant project where you come to it. And I showed the video to Theresa, the video I took that day of your work to Teresa, and she thought was brilliant as well. So it's sustainable. The pieces in theory should be easily replaced. It has the game focus, kind of that incentive to learn and to figure out and to create, problem solving. It has all those things in it. Fun, and it looks good. It looks engaging.

Annika 45:05

Thank you very much.

Maria 45:08

Its very cool, very cool. And it's all ages as well. It's all ages. Now, you were very familiar with the pieces, so you clicked it together really quickly. Someone who's not familiar with it is going to have to spend time. I would worry that it might be too challenging for a child. Yeah, the age of the child, but, yeah, great foundation.

Annika 45:34

I tested, I gave it to my boyfriend before, and had him kind of put it together, because I thought it was way too easy. And then he did, and he was actually struggling with some of the bits. And I was like, oh.

Maria 45:47

Yeah, I can see that. It's like second nature to you at this point.

Annika 45:50

Yeah because, I know exactly where they're going. And it's like, oh, that's actually good to know. So I reduced the pieces by two, because I immediately noticed, okay, that was where

he was struggling with, and then later on, I kept it now at that, but I know exactly that if I wanted to make it easier again, there'd be two pieces that I'd get rid of and that would probably make it more for children.

Maria 46:13

You would just make them one.

Annika 46:17

It's the skirt part. People make the statue a lot shorter because they forget that there's a leg. Which is, I found really interesting. That's then something, if I do extensive user testing, and then I obviously, if you ever implemented properly, you would test children. I know I'm not allowed to. Or even just making two puzzles, having one for children, or one for where you say beginner, one little bit more advanced, and everyone can see what they want to do themselves, how far they want to challenge themselves.

Maria 46:54

Absolutely, yeah. But even in terms of education resources, here, you know, age appropriate ones. We have series of loan boxes that schools borrow. And so we have pre Christian one, Christian being prehistoric, and one on the Vikings. And there we have series of replica objects, no 3d printed objects in them, yet, but replica objects and a puzzle like you have there would, it would be a really lovely addition to an existing resource like that, you know? Yeah, there's the you can take so many directions.

Annika 47:36

Yeah, it's a very adaptive design.

Maria 47:39

And scale as well. We're getting people to, you know, that kinesthetic kind of and getting them to move their bodies. You can scale this up and down.

Annika 47:50

Yeah, I'm happy where it is for now.

Maria 47:51

Yeah, great project. see where it takes me. There's huge potential there. That's for sure.

Annika 47:58

That's everything from me. Would you like to add anything else?

Maria 48:01

No, no, I don't, I don't think so at this point. But I enjoy the chat. Thank you.

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